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PREFACE

This issue represents the first step in the transition from an annual to a quarterly volume of A. I. E. E. TRANSACTIONS. The amount of technical papers published annually by the Institute has been constantly increasing, and during the past year reached a volume that could not economically be bound in a single book. To avoid discarding a large number of acceptable papers in order to keep within the limits of a single book, it has been planned to issue the TRANSACTIONS quarterly, in pamphlet binding, which makes them eligible to entry as second-class mail. A limited number of the quarterlies will be bound in cloth to meet the demand of those who desire a more permanent binding, for which an additional price is charged. Aside from its mechanical make-up the quarterly TRANSACTIONS will be exactly like the former annual volumes as to their contents, which will consist, as heretofore, of those papers and discussions presented before the Institute that are judged worthy of being included in its permanent records. It is believed that the present plan will take care of the increasing publication demands for several years.

Advance Planning of the Telephone Toll Plant

BY J. N. CHAMBERLIN[1]

Member, A. I. E. E.

THE advance planning activities of a large telephone company is a field of endeavor that perhaps is not very generally understood by those not intimately associated with the communication art. This may be due to many circumstances, the more probable of which is the fact that telephone service has grown to be one of the necessities of social and business life and, from casual observation, seems to differ but little in individual locations. In the small or large community, similar subscribers apparatus is in general use; wires and poles of like character are in evidence and service is apparently rendered in much the same manner. These observations are basically correct. In structural design and operating practises, however, widely different problems are encountered in the rendering of service in separate communities.

Satisfactory service to the customer and economic operation in all locations require continuous study of both the present and probable future service demands, operating practises and characteristics of the physical plants design. In the small communities or exchanges, as they are called, problems of less complexity are encountered than in the metropolitan areas. The solution of these, however, whether they be large or small, are important functions of successful operation. Small exchanges grow and change in character and the telephone company must so plan its activities as to meet satisfactorily the future conditions as they may present themselves and at the same time, provide a financially sound structure in the rendering of a universal service. As a community develops and more service is rendered, more than proportionate amounts of capital and labor are required in providing the service for each additional customer. Interconnecting devices or switchboards are limited to a definite number of subscriber's lines. When the switchboard's capacity is reached, new offices or replacing switchboards of larger size are required. The number of operators employed is dependent upon the amount of service rendered and as service demands increase, more operators are employed. Pole line, wire, and cable are installed as needed to meet the expected future requirements of customers. The character and extent of this part of a telephone structure are governed by the size and density in population of the area served.

The average individual, not fully informed in the complexity of telephone equipment or the details of operation, is very apt, in his appraisal of the business, to use as a unit of measure, the telephone instrument. He fails to realize that, in a telephone system, separate and complicated pieces of equipment are permanently assigned on the switchboard to individual subscriber's lines and that large amounts of equipment and apparatus are required for the establishment of an independent channel of communication for each pair of talkers. The telephone instruments, channels of communication and switchboards are the mediums through which service is rendered. Therefore, the three components rather than any individual one should be used as a unit in a general analysis. Service, on the other hand, is what is being offered under the various tariffs and it, rather than any of the physical properties, is a more correct measure of value. If service is restricted as to hours, distances and types, the cost of rendering it lessens; likewise its value to the user.

The term "telephone plant" very aptly describes the structure by which communication service is rendered. It is ever varying in its charactristics and must grow in size and nature in a manner consistent with the demands resulting from the population within the area served. When people move into or within a community and want telephone service, the company must be prepared by the extension of its lines to give the service. As compared with other utility fields, the telephone business is somewhat unique in that applicants for service are not the only ones interested in obtaining it. The value of the service to those who already have it, is of course increased by the number connected with the system. Also the service rendered must always satisfy two individuals rather than one and must be available at such time of the day or night and for such duration as the customers, themselves, may elect.

During the pioneering days of the telephone business, little realization could be had of the development of the art to the state in which we find it today. To attempt, at the present, a detailed prediction of future attainments would result in but individual theory and is in no way herein attempted. Effort is to be made to simply set forth, in a very general manner, some of the fundamentals that are used today in advance planning, particularly as they concern long distance telephone service. In doing this, it will be necessary frequently to refer to some of the fundamentals underlying local or exchange plant planning, as such activities are intimately related to the planning of long distance service.

While similar to other structures in many ways, a long distance telephone plant is quite dissimilar, especially in regard to the ever present indeterminate demand that may, without any appreciable warning, be placed upon it. Local disasters and climatic disturbances repeatedly give rise to heavy service demands. These can, in no way, be anticipated as to time or im-

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portance. Their occurrence, however, must be expected and means provided in a general way for caring for these occasional surges in demands for service. Seasonal loads resulting from accelerated business activities occur at different times of the year in widely separated localities. The demand for service to and from recreation resorts during the summer months presents another rather indeterminate demand for service. These latter loads, as they are termed, can be better anticipated than the former as their annual recurrence can be made a matter of record and their characteristics closely studied.

The linking together of two separate communities of meager population, as was repeatedly done in the past, is incomparable with the demands for the network of circuits made upon the telephone company of today by the ever growing metropolitan and suburban areas. Closely allied to the demand resulting from increased population is the growing demand as a result of the increased use of the telephone in business and social activities.

Experience has indicated that the telephone service grows much more rapidly than the population because of the necessity of meeting the service demands of not only the new population but also the increasing demands of the existing population. The term "population" as herein used denotes families, rather than a per capita population, it being obvious that such a unit is more closely related to communication service requirements than would be a per capita unit.

It is, therefore, a function of good telephone management to estimate population increases as accurately as is possible in advance in order that facilities may be extended with confidence that the future service demands will be satisfactorily met and that they will be handled along basically sound lines and with maximum economy. This requires what are termed "commercial surveys" or "development surveys" which are detailed estimates of future expectancies. The compilation of these surveys demands a large amount of field work, the tabulation of existing statistics and forecasting of the probable changes in amounts and distribution of the future population. Analyses are made of the amount of the past growth and of the reasons for this growth. The factors affecting future growth are considered and evaluated, and estimates made of the most probable future population growth.

As any estimate of future population may be in error, due to occurrence of some unpredictable event, it is highly essential that the management be ever on the alert to observe the first indications and the importance of changing circumstances and conditions. Selected and highly trained personnel, therefore, are continually employed in analyzing the economic and business conditions of the community being served and are closely studying the details of the probable moves of population within and between both urban and suburban areas. Such prophecy as an estimate of the probable redistribution of the population as will result from better roads or improved transportation facilities between communities is a typical example of this development engineering. Another example and one which is highly important in local or exchange line development survey activities, is the forecasting of the effect that will result from the constant change of individual properties from residence to apartment house and business purposes.

The estimates of future population are made of individual communities for a major portion of the area served and forecast the probable population for several periods into the future. These estimates picture the size, distribution, and character of the future market for telephone service. Additional estimates of the service demands from this market must then be made so that the final estimates may indicate the probable number of telephones that will be required at different future periods. As both individual and party line service are usually offered in an exchange area and telephone plant investment and operating costs vary in the rendering of the several grades of service, it is necessary to proceed further with the prediction of the estimated "telephone development" by classifying it into the various types of service rendered. After this has been accomplished these data are transcribed in numerical form to large scale survey maps covering the area being studied. These maps are called "telephone line distribution maps," and serve to indicate the density and approximate location by small areas of the total number of anticipated subscribers lines.

When the features of the development survey necessary to prepare the line distribution map have been concluded for individual communities, it is necessary to then make predictions as to the amount of service that will result from the estimated telephones. In telephone language this means the determination of the "calling rate" or average use of the service per customer's station. In small communities this is not a feature of major concern. In the metropolitan areas, where several operating central offices are maintained, it is a highly important function in developing the detail design of the future plant structure.

Interrelated and associated with the study of calling rates in a multi-office exchange area is a further activity which has to do with the forecasting of the direction of the flow of service between the several operating areas within the exchange. Between adjacent central office districts there usually exists a different community of interest among the customers than between non-adjacent offices or between residence and business areas.

The ratio of the present telephone development to the population, location, average number of daily calls per customer's station, and the direction of flow of the past service is, of course, a matter of record. These statistics are extensively used in making predictions but in no way preclude the necessity for the exercise of sound judgment in forecasting the probable future

trend of service demands and characteristics. Upon the results of these series of studies and forecasts, operating plans are adopted and construction details determined. It is therefore, apparent that this portion of advance planning work is a highly important part of telephone engineering.

In the exchange lines or local plant planning, these data are used to prepare basic plant layouts to be used as guides in construction and future extension work. These plant layouts, or "fundamental plans" as they are called, depict both present and anticipated future central operating centers, local service limitations, economic plant arrangements, and such other pertinent data as may be reasonably forecast. Their preparation requires a large amount of time and study by a personnel that has a thorough knowledge of telephone fundamentals. Detailed consideration in these studies is given to the determination of the ultimate number, size, and location of central offices. Comparisons are made of various types of equipment, operating methods, and construction details. The wire mileage required in concentrating the subscriber's lines as indicated on the previously mentioned line distribution map under different plans are determined, land values and costs of construction and maintenance estimated and studied before the selection of a plan is undertaken. In exchanges requiring but one central office, these tasks are comparatively simple. In the multi-office exchange, however, and those approximating such size, many additional factors, such as trunk and tie lines between central offices, present themselves as influencing factors in arriving at an ultimate decision. Many other features of importance are concerned in these fundamental plan studies but cannot be dealt with here in the time allowed for the subject in hand.

In long distance or toll line advance planning, these same data are used in the formulation of a long range basic toll line plant layout or toll fundamental plan. In these latter studies, however, it is necessary to analyze, among other things, the flow of calls between, rather than within, individual communities. How service between separate and distant areas is to be handled, where interconnection between circuits and recording is to be done, and how many circuits will be required to satisfactorily serve the long distance service demand over future periods of years, are the desired conclusions to be obtained from these studies.

The item of cost in relation to service finds its fullest application in these fundamental plan activities. Advancement in the art is to be anticipated and the cost of all progress must be judicially interpreted and forecast. Technical development is of necessity an all important factor in the giving and extension of communication service. Its mastery, however, in no way excludes the study of economies; on the contrary, it creates economic problems that require extensive study and ultimate solution before general application can be made of any individual improvement.

Many different general plans of varying details present themselves for solution during the activities concerned in these studies. These must be independently worked out and comparisons made, both from the service and cost viewpoint, before conclusions are formed. This is done through the medium of engineering cost comparison studies which usually express in terms of equivalent present worths, the total costs of the different plans over an extended cycle of years. Special problems concerned with detailed features of individual additions to the plant structure, quite naturally cannot be intimately dealt with and fully set forth in a general study of basic fundamentals. These must be studied as they arise during current activities dealing with changes and additions to the plant and their solutions obtained through individual study.

The engineering cost comparison study, in which the initial investment, deferred investments, annual charges and credits for future salvage returns of different plans of comparable design are analyzed, is a most important element in future planning. The initial and deferred costs of the different plans are usually very readily obtained. The annual costs and salvage credits to be anticipated at the termination of the service life of the plant structure are more difficult of correct interpretation. They are, nevertheless, of equal importance in the solution. Similar to all analyses of future cost factors, these engineering cost comparison studies involve the making of definite assumptions of future anticipation. Due to the climatic and human elements, that continually affect the service life and maintenance expense of a large part of a telephone company's investment, it is highly essential that the assumptions in these studies be based upon an intimate knowledge of present and anticipated factors, and that proper decisions be made in appraising the results that are indicated at the conclusion of the studies.

It is very necessary in their interpretation, therefore, to give thorough consideration to many intangible elements. A few of these may be cited as follows:

1. The practicability of the several plans under possible future changing conditions.

2. The adaptability of the separate plans to existing plant units and to future technical advancement.

3. The new money required to put the individual plans into effect.

4. The weighing of assured immediate economies of one plan with the estimated future economies of other plans.

There is no simple method for determining exactly how many toll calls will flow to or from individual communities. The experience of competent engineers and a thorough study of past and present statistics and related forecasts is the best available guide in planning for the expansion of the service. Extensive records are kept of the average number of long distance calls placed per customer's station; of how the originating traffic of individual communities is distributed over

existing circuits; of the time consumed in making the desired connection or interconnection, and the average time the circuit is held for conversation.

For the purpose of planning, schedules of the call carrying capacity of the circuits under different operating methods and under different conditions as regards service delays have been formulated. Their application varies with the length of the circuit, number of circuits in a group, and the ratio of direct calls-to-calls requiring built up connections. In planning for the future, these theoretical circuit capacity schedules are set up on a premise of a different degree of freedom from service delays, on account of no circuit conditions, occurring on a given number of calls. By a no circuit condition is meant that all circuits in a particular circuit group are in use at the time a connection is desired.

The determination of future circuit requirements over long term periods is carried on by the use of these schedules and the estimates of future traffic. In predicting the immediate necessity for circuit rearrangements and additions they are, however, modified to meet the circumstances under individual review. As operating conditions and local service demands result in a considerable varying of speed of service and circuit capacity between individual communities, it is necessary that intensive study be given to individual groups. Such matters as the size of the circuit group, the type of service to be rendered, the average length of conversation, and the distribution of the traffic through the hours of the day, must receive careful consideration.

A record is usually taken over a period of 20 business days during the month, in which the distribution of the traffic is representative of the conditions for which the plant is to be engineered. When encountering conditions that are not similar throughout the territory, this record is adjusted for the different seasonal conditions. As circuit groups do not experience their greatest traffic in the same month or maintain the same trend throughout the year, supplemental checks of the traffic volumes are made. Ordinarily additional circuits are provided less liberally for groups showing a traffic peak of relatively short duration than for groups carrying heavy traffic over periods of two or three months. These checks are also studied for the purpose of determining the possibility of overflowing traffic to groups having margins and of rearranging the circuit layout either temporarily or permanently to meet fluctuations.

These detailed studies of circuits and load characteristics have been used extensively in the past in determining the immediate and early necessity for circuit rearrangements and additions to individual groups. Today it is necessary to use them as a guide in the projection of future requirements over long periods of years. This is due to the changing design of long distance telephone plant and is made necessary by the installation of a large portion of the circuit facilities on a somewhat different basis than in former years.

Until a comparatively few years ago, practically all long toll circuits were of open wire construction; that is, individual wires separately attached to crossarms on the poles. These have been installed as required and were a natural development due to the small number of circuits required to handle early day long distance demands. The wires have very generally comprised two sizes, namely, No. 8 Birmingham wire gage, (165 mil.), weighing 435 lb. per mi., and No. 12 New British standard gage, (104 mil.), weighing 173 lb. per mi. These two types of uninsulated wire have admirably lent themselves to the many changes and improvements in the communication art. For many years the limits for the highest grade service with these conductors were approximately 400 and 200 mi., respectively. The development of associated equipment, however, has so increased the distance over which service may be rendered with these sizes of wire, that today finds them in general use over distances of thousands of miles.

The introduction of the inductance or loading coil on open wire circuits, many years ago, so reduced the attenuation loss of open wire circuits that satisfactory voice communication was greatly extended in range. Distance of transmission on open wire circuits was later further increased by the installation of the mechanical repeater into the circuit to be used in conjunction with the loading coil. Experience, however, soon indicated that improvement must be made in the uniformity of the amplification given by the repeaters in order to raise the intelligibility of the voice transmission to a higher standard. This led to the use of the vacuum tube repeater which economically and satisfactorily eliminated the limitations of the mechanical type repeater. As a result, the vacuum tube repeater soon replaced the mechanical type and is today exclusively used in voice amplification.

Improvements and modifications in the design of the repeater and reduction in its cost of manufacture have made it desirable and economical to use it more frequently on long-distance lines in lieu of the loading coil. At present, therefore, we find the use of the loading coil on open wire lines very generally restricted. In its place is found the vacuum tube repeater, with service range increased and quality of transmission improved.

The non-loaded No. 165 and 104-mil open wire circuit have also permitted the development and use of the higher frequency ranges in voice communication. Without distortion or sacrifice to the quality of the service, frequencies ranging up to 30,000 can be used on non-loaded repeatered open wire lines. The application of these higher frequency ranges to what are termed "carrier current systems," in voice communication, has extended the field of use of the open wire circuit many fold. In brief explanation of this statement, a

typical open wire line, carrying four fully equipped ten pin crossarms, is capable of providing the following voice channels. Four crossarms supporting 40 wires of the standard configuration of 12-in. horizontal and 24-in. vertical separation, when properly transposed, produce 20 physical and 10 phantom circuits or a total of 30 voice-frequency talking circuits. By the proper coordinating or additional transposing of 8 of the wires on the top crossarm four carrier current systems can be superposed on the 8 wires. As each system is capable of producing 3 speech channels a total of 12 additional circuits is thus provided. Without any loss in the number of voice frequency circuits on the lead four similar carrier systems with like circuit possibilities can be superposed on eight wires of the third crossarm. This complete arrangement therefore increases the speech channels on a 40-wire line from 30 to 54 circuits or nearly one hundred per cent.

Carrier current telegraph systems of ten channels each can also be similarly superposed on the open wire circuits, thus in another manner greatly extending the use of open wire for communication service. At the present time it does not appear economical, due to the excessive expense of balancing the open wire for purpose of eliminating interference or "cross-talk" to superpose telephone carrier current systems of the three channel type on adjacent crossarms.

These three-channel carrier systems require highly expensive terminal equipment and well insulated and evenly balanced open wire lines. The economy of their installation generally speaking is confined to lines of 150 mi. and over in length. Often however, major reconstruction work on a pole line that would be required by additional open wire placements can be advantageously deferred by the judicious use of the carrier systems. Recent developments in high-frequency systems have resulted in a new system of one channel. This type is proving economical for superposing on open wire lines of approximately 50 mi. in length.

The rapidly increasing demands for toll service several years ago indicated many difficulties in providing for future long distance communication service on a wholly open wire basis. The number of open wires that can be placed upon a pole line is limited. The number of pole lines that can be constructed along highway routes is restricted and the costs of purchasing private rights-of-way for open wire lines is becoming excessive. These conditions prompted the development of some other practicable method of providing for the increasing number of toll circuits.

To meet this situation, effort was made to provide means which would permit of satisfactory conversation over long lengths of cable. In other words it appeared desirable to provide along one path a greater number of circuits of a type that require less space and structural support. In this endeavor highly successful results have been attained. Satisfactory conversation can now be given over an extended network of cable plant. Repeater operation appears to have solved the problem of distance and in so doing has made possible reductions in the use of copper to approximately 10 per cent of the amount used in open wire circuits of equal length. For example instead of the No. 8-gage open wire weighing 870 lb. per circuit mi. and the No. 12-gage weighing 344 lb. per circuit mi., the conductors, which are extensively used today in cable design weigh but 80 and 40 lb. per circuit mi. In the cable type of construction from 100 to 300 voice frequency circuits are provided in a cross sectional area of less than 6 sq. in. To accomplish this, relatively small gage wire must be used and some dielectric other than air must be provided for maintaining separation of the wires.

Two types of cable conductors present an economic balance at this time for general use. These comprise 16-gage wire, weighing about 40 lb. per mi. and 19-gage wire, weighing about 20 lb. per mi. These wires are each individually insulated by means of a spiral wrapping of paper ribbon of approximately 0.004 in. thickness and 0.625 in. in width. The wires are twisted into pairs, the pairs laid up into groups of 4 wires, termed "quads" and the "quads" stranded together and enclosed in a lead-antimony sheath of approximately 1/8 in. in thickness. In a large portion of toll cable installations it is found economical to provide a complement of both sizes of conductors in an individual cable sheath. This feature can be determined only after an extensive and detailed study of the use to which the individual circuits are to be placed. In a majority of instances comparisons must be made as to the economies of a larger gage with those of a smaller gage provided with a greater number of telephone repeaters, it being possible to obtain the same grade of circuits having given characteristics, by either size of conductor equipped with a different number of repeaters.

It is conceivable, although obviously impracticable, to design all circuit groups on a toll lead as individual units. Practical operation requires the centralizing of loading coils and repeaters at a minimum of locations. In the average cable installation loading coils are placed at regular intervals of approximately 6000 ft. and repeaters at approximately 50 mi. intervals. In locating these latter, consideration must be given to housing facilities as from one hundred to several hundred repeaters are usually installed at a given location. They must also be located in close proximity to the location dictated by electrical requirements.

Toll cable construction presents many advantages over open wire plant. It provides at one time an equivalent number of circuits that are offered by seven or eight open wire lines. The ever annoying foliage interference occasioned on open wire circuits passing through wooded sections is largely eliminated by cable construction. Of major importance also is the relief afforded from service interruption occasioned by sleet

and wind storms and the resultant costs of the restoration of service.

Thorough studies of the economic design of toll cables are important before proceeding with an installation. Due to the many circuits provided at one time and the relative high cost of cable construction it is necessary in economic planning to design a cable to serve for an extended period of years into the future. This requires not only an intimate knowledge of the present use to which an individual cable is to be placed but also a well coordinated plan of its fitness to form an important unit in an ultimate cable network.

In long-distance wire communication, therefore, consideration is given in advance planning to the provision of three types of service facilities. Between the scattered and sparsely settled areas, the open wire circuit is at first provided. As demands for more service are encountered additional facilities are provided by means of more open wire or the superposing on existing wire of carrier current systems. Between the well developed and fast growing areas, however, where an extensive network of circuits is already in service the matter of planning for future additions is a decidedly different problem. Here is encountered the solving of many problems relative to the continuance of open wire construction versus toll cable installation.

Questions of route, both as to desirability and permanency of location are of major importance in designing additions and changes in the character of construction. In the early days of the telephone business this was not a matter of great concern. With electrical development in the power and communication fields and the gradual extension of both services, the problem of the coordination of the network of wires makes necessary an intimate study of the induced disturbances that may result when wires of either service are located in close proximity to wires rendering another type of service.

Many fundamental differences exist between power and telephone transmission systems. The former transmits large amounts of power usually at relatively low frequencies while the latter transmits speech waves through the use of a very small amount of electrical energy at a comparatively high frequency. Even with the use of relatively small amounts of electrical energy in wire communication, the economy of placing circuits close together and of superposing several channels of communication on each pair of wires, justifies and requires an elaborate scheme of coordination between the telephone wires themselves to eliminate mutual interference between channels. These requirements are closely related to those for prevention of interference from external sources. Induced disturbances from electrical circuits rendering other services, when in close proximity to communication channels, may seriously interfere with satisfactory voice transmission and cause interruptions to service, damage to plant, and hazard to personnel.

This subject of interference from other sources has been extensively discussed on previous occasions. Reference is made to it in passing for the purpose of indicating the continued importance of coordination work by those concerned in the advance planning of telephone and power long distance service. If the more general use of toll cable construction should eliminate the inductive coordination problem of today it would indeed be fortunate. Such attainment however, cannot be anticipated. Freedom through separation from other electrical circuits and the cooperation in the application of remedial measures by all wire using companies must continue to be effected in the planning, maintenance, and operating practises of the different electrical systems. In the advancement of such cooperative effort notable contributions have been made by the interutility joint committees, such as the General Joint Committee of the National Electric Light Association and the Bell Telephone System.

Other problems, not of an electrical nature, are concerned with the construction details of both open wire and toll cable installations. Pole structures must be designed to withstand not only the dead weight of the anticipated attachments but the storm stresses that may occasionally be experienced. These of course vary in different locations and are an individual field of study and research. Studies of this nature are not confined in particular to the telephone business but they are an important element in the work of rendering proper service. Sub-surface structures, such as conduits and splicing vaults form a large item of investment in all telephone companies plant. This type of construction is rapidly being extended, particularly in connection with extensive toll cable conditions. Underground conduits, into which cables may be drawn, offer reasonable permanency of location and freedom from fire destruction and the devastating effects of climatic disturbances. In order to obtain economies in underground construction however, it is necessary to provide for many years into the future; therefore well established fundamentals must underlie any major conduit installation. In this connection it differs from the other branches of advance planning work only in that it usually concerns the provision of a type of plant for greater periods into the future.

The results obtained by making the studies which have been very briefly discussed indicate the anticipated relative economies of the future plant structure under assumed conditions. It is necessary however, before undertaking any major plant work, particularly if large expenditures are involved, to formulate a well balanced and orderly construction program. This is a very essential part of advance planning. Materials and labor must be available at widely separate locations and at prearranged periods and all unfavorable reactions to the service while carrying on the construction program must be avoided. For purpose of indicating the scope of these planning activities and their results the

following brief review is given of a portion of the Pacific Telephone and Telegraph Company's present toll plant structure and current extension program.

In the Northern California area of the Pacific Company's territory, comprising a majority of the communities in the State of California situated north of the Tehachapi Mountains, there are some 380 separate company operated exchanges. These vary in size from the small hamlet of a few inhabitants to the large cities of several hundred thousand population. Interconnecting and serving these localities with long distance telephone service are 178 main or toll center groups of circuits and 424 so called tributary circuit groups. At the present time most of these are in open wire construction. In planning for the future, quite naturally the major problems center around the larger and more rapidly growing groups. Correct solution of the future service on these groups however, cannot be obtained without thorough consideration being given to the tributary groups. This is being carried on by members of the Pacific Company's staff. Many circuit miles of open wire construction is included in the future program. Extensive carrier current systems are contemplated and approximately 1000 mi. of toll cable installation is being designed for the provision of service over the next 10 year period.

Within the past 12 months a 90-mi. section of this cable network has been completed between the San Francisco Bay area and Sacramento, California. The cable was designed to provide 295 voice communication channels for rendering service to Sacramento and points north and east. Liberal provision was also made for service to intermediate points. The cable is of 19 and 16 gage design, is equipped with loading coils at intervals of 6000 ft. and is provided with repeater service at the town of Crockett, located 30 mi. northeast of San Francisco. The repeater station is equipped at the present time with 100 repeaters and is designed to house approximately 200 additional repeaters over the next few years. This toll cable has been designed for extension northward and eastward at a future date, at which time it will form an intimate unit of a cable network extending very generally throughout the State of California.

In the 1000 mi. of toll cable network included in the present program, studies indicate the desirability of proceeding with the installation of approximately 100-mi. of cable per annum. A large part of this will be along existing open wire routes, although considerable relocating will be required and many underground sections will be constructed.

In the San Francisco Bay area there exists today an extensive toll cable network. This provides cable circuits to and between surrounding communities and toll entering facilities for the long distance open wire circuits radiating from the San Francisco Exchange. The continued maintenance and future planning of a large portion of this network presents an additional and independent problem, not previously referred to and not very extensively encountered in other localities. This has to do with the planning of a large amount of submarine cable plant.

San Francisco Bay is an extensive body of water, both in area and depth. To cross it at strategic points with communication service and place the necessary plant structures in reasonable permanent locations, requires the use of submarine cables of closed sheath lengths of from 10,000 to 13,000 ft. These cables must be maintained at depths ranging to 200 ft. In the crossing of the Bay from San Francisco to the East Bay communities, a water distance of approximately 4 mi., two 10,000 ft. sections are required to form an individual cable. The presence of Yerba Buena Island about mid-distant makes it possible to so sectionalize the cables into two units. This is a fortunate circumstance as advantage can be taken at the shore of the island to install cable loading coils.

In the short haul circuit groups rendering transbay service between the Bay area communities there are in use at the present time approximately 1400 circuits. Some conception of the magnitude of this number of voice frequency circuits may be obtained by realizing their equivalent number expressed in open wire. Were it possible to render this transbay service with standard open wire construction there would be required 24 individual pole lines each supporting 8 crossarms of 10 wires each.

Until a comparatively short time ago all circuits entering and leaving San Francisco, with the exception of one very short circuit required in their path the use of submarine cable. This was a very undesirable situation due to the ever present hazards to that type of plant and the serious service interruptions that usually accompany a submarine cable failure. Recent local developments and major toll underground cable extensions, have made possible a partial change in this regard, although it will continue to be necessary in providing future additional service to install and maintain a large amount of submarine plant and equipment.

In the advance planning of these submarine facilities attention is given to the judicious safeguarding of the plant and to the adoption of such operating methods and arrangement of circuits that will require a minimum number of submarine cables. As the volume of service over individual circuit groups and plant conditions permit, circuits previously interconnected at or switched through San Francisco, are otherwise routed. While the development of economies that may be anticipated from a change in circuit routings is an important part in the advance planning of other parts of a telephone plant, as previously referred to in the fundamental plan activities, it is of major importance in the planning of toll circuits across San Francisco Bay.

Many other and equally important features of

telephone long distance advance planning could be set forth in this discussion. Those of an electrical and mechanical character have been often presented in various forms and therefore have been omitted. This has been done with no intent to stress the importance of any part of the activities concerned with the advance planning of long distance service but more in an endeavor to set forth briefly certain fundamentals of the work that are not generally realized by those not connected with telephone work. While classed a branch of the electrical profession, telephone planning and operation comprehend important elements not at all electrical in their character. Electrical phenomena and their adaptation to the art of communication are essential features, but of equal importance is the solution of problems unrelated to the electrical science. Successful management of a telephone company as a result of these circumstances, depends in part upon the study and application of electrical accomplishment, in part upon the analysis and forecast of economic conditions prevailing and anticipated in the area being served with communication service, and in part upon the solution of mechanical problems relating to the construction and maintenance of a plant structure, the whole combined to render an economic service and produce a fair return on the investment.

Discussion

For discussion of this paper see page 20.

Tandem System of Handling Short-Haul Toll Calls In and About Los Angeles

BY F. D. WHEELOCK[1] Associate, A. I. E. E. and E. JACOBSEN[2] Associate, A. I. E. E.

Introduction

In telephone practise there are, broadly considered, two distinct methods of completing telephone calls between central offices, one by means of direct trunking and the other by means of tandem trunking. The fundamental difference between these two methods may be best obtained by referring to Fig. 1. It will be noted that direct trunking, as the name implies, requires a separate group of trunks from any one office to every other office, whereas tandem trunking provides for a single group of trunks from each office to a centralized point, known as the tandem center or office, at which are means for switching together any desired combination of trunks. Under the direct trunking plan, 30 groups of trunks are required to interconnect completely the six offices illustrated, while under the tandem trunking arrangement only six groups are necessary. The tandem trunking plan has the advantage that the trunk groups are comparatively large and therefore can be used more efficiently. It is obvious that the advantages of tandem trunking become very marked as the number of offices to be interconnected increases.

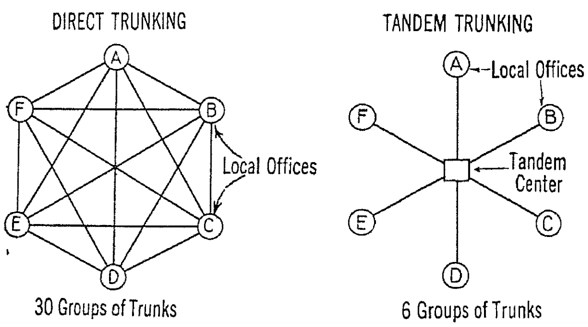

Fig. 1—Trunking Plans

A great many tandem systems are in operation today where the switching at the tandem office is done manually. There are a few installations where a moderate amount of tandem switching is done automatically. The first tandem trunking system to employ, on a large scale, apparatus for switching which is under the control of dials located at the various operators' positions tributary to the tandem office, was recently installed at Los Angeles to handle the short-haul toll traffic within a radius of approximately 40 mi. This system is known as a dial tandem system.

It is the purpose of this paper to describe the Los Angeles dial tandem system. A brief description is first given of the telephone area of southern California and of the various methods which existed for completing short-haul toll calls, and is followed by a discussion of some of the considerations which led to the adoption of the particular type of tandem system in question. A detailed description is then given of the equipment employed at the tandem center and at the outlying points, together with a method of operation.

It should not be inferred that a system similar to the one installed in Los Angeles should necessarily be regarded as suitable for other large cities, as there were certain conditions in this area, described later on, which made this type of installation particularly desirable.

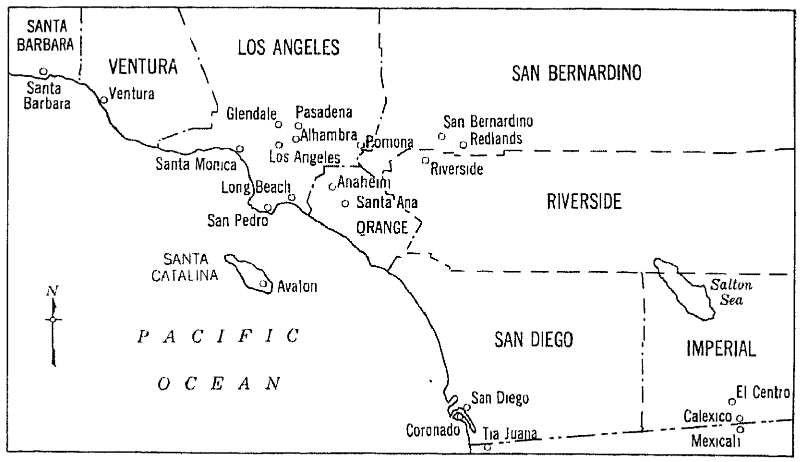

Fig. 2

The Handling of Short-Haul Toll Traffic in the Area of Southern California Prior to the Installation of the Dial Tandem System

The portion of the area in southern California in which short-haul toll calls are handled is approximately 300 mi. in length, along the Pacific Coast, varying in width from 5 to 100 mi., limited by ocean, mountainous contour and desert stretches, extending from the northern Santa Barbara County line to the southern international boundary. This area of approximately 24,000 sq. mi. is shown in Fig. 2 and consists of all or parts of the following California counties:

Santa Barbara	San Diego
Ventura	San Bernardino
Los Angeles	Riverside
Orange	Imperial

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1. Southern California Telephone Co., 940 S. Olive St., Los Angeles, Cal.

2. American Telephone & Telegraph Co., 195 Broadway, New York, N. Y.

Presented at the Pacific Coast Convention of the A. I. E. E., Del Monte, Calif., September 13-16, 1927.

See Journ of AIEE of Dec 1927 Pp 1415-1422

These eight counties increased in population from 1,347,000 in 1920 to 2,412,000 in 1927, while the city of Los Angeles, alone, nearly doubled its population in the same seven years, from 612,000 in 1920 to 1,210,000 in 1927.

There are 145 telephone exchanges in the area varying in size from less than 10 to more than 325,000 stations. The type of local equipment and number of offices in these exchanges are:

42 Magneto manual offices
20 Small common battery offices
68 Large common battery offices
57 Dial system (step-by-step) offices
9 Semi-automatic offices (machine switching equipment controlled manually by means of operators).

In addition to, and separate from, the local, there are one or more toll boards located at the following places:

Alhambra	Long Beach	San Diego
Anaheim	Los Angeles	San Pedro
Corona	Pomona	Santa Ana
Covina	Oxnard	Santa Barbara
Downey	Redlands	Santa Monica
El Centro	Redondo	Ventura
Fullerton	Riverside	Whittier
	San Bernardino	

Notable outposts in our national telephone system, to which local toll calls to and from this area are completed, are Avalon, Catalina Island; Tia Juana, Mexico; and Mexicali, Mexico.

There is in the area, terminating at manual toll positions and at dial tandem equipment, a total of 3148 toll lines and 3294 trunks representing 52,866 circuit mi. of cable, 27,950 circuit mi. of open wire, and 1633 circuit mi. of telephone carrier. There are two toll offices in Los Angeles, one consisting of 222 positions, handling both short-haul toll and long distance calls, and a smaller office consisting of 96 positions, handling short-haul toll calls, exclusively.

Previous to 1919, short-haul toll calls in southern California were handled via toll switchboards with the exception of those between Los Angeles, Glendale, and Pasadena. The latter calls were handled either by direct trunks or by tandem trunks. Following this, some dial equipment was made available in Los Angeles, Santa Monica, and Long Beach, which permitted direct calling from the Santa Monica and Long Beach toll boards to Los Angeles dial stations. Certain Los Angeles toll board positions were also arranged for direct calling of all Santa Monica stations. In 1924, three Los Angeles toll board positions were arranged for straightforward tandem trunking for handling a portion of the short-haul toll calls from Los Angeles to Alhambra, Inglewood, Long Beach, Montebello, San Pedro, and Wilmington. In the same year it was necessary to make rather extensive provision of toll switchboard equipment to take care of the large amount of tributary toll traffic recorded in Los Angeles from Alhambra, Arcadia, Burbank, Compton, Covina, Cresenta, Downey, El Monte, El Segundo, Gardena, Hawthorne, Hynes, Inglewood, Lankershim, Monrovia, Montebello, Owensmouth, Redondo, San Fernando, Sierra Madre, Sunland, and Torrance.

It is apparent from the foregoing that a considerable number of channels existed for the handling and the completion of short-haul calls summarized as follows:

1. Calls recorded at toll boards via:
   a. Toll board and ringdown toll lines,
   b. Toll board and limited toll line dialing arrangements,
   c. Tributary recording board and toll lines.
2. Calls recorded at local boards:
   a. Direct trunks,
   b. Local tandem trunks,
   c. Straightforward tandem trunks and toll lines.

1. Calls Recorded at Toll Board.

a. Toll Board and Ringdown Toll Lines.

On originating person-to-person calls the subscriber's line was connected by the local operator first answering to a trunk terminating in the toll offices at segregated positions for recording the subscriber's call. The toll ticket prepared there, was passed to a line position arranged for completing toll calls to outlying exchanges. The line operator then connected the calling subscriber over a special trunk known as a toll switching trunk to the called party over the ringdown toll line terminating at an inward position at the distant exchange. Number service calls made use of similar equipment, except that the recording trunk terminated in the toll office at a particular position arranged for both recording and completing. The toll line on inward calls, whether person-to-person or station-to-station, was connected by the inward toll operator directly to the subscriber's multiple or over a toll switching trunk, to the called station.

b. Toll Board and Limited Toll Line Dialing Arrangements.

Toll calls completed by the limited dialing arrangements were identically handled, and required equipment similar to that described in the preceding paragraph, except that the toll line dialing equipment permitted the operator at the originating end to dial and obtain the called station at the distant end without passing through the inward toll board.

c. Tributary Recording Board and Toll Lines.

The toll calls from nearby outlying points that were handled at tributary recording boards, terminated on toll line equipment at the toll center on positions arranged for recording and completing. The toll line was there connected over a toll switching trunk to the called station, or if the call was to another exchange the line was connected to another toll line terminating at an inward position at the distant exchange.

2. Calls Recorded at Local Boards.

a. Direct Trunks.

On an originating call completed over direct trunks, the subscriber's line was connected by the local operator first answering to interoffice trunk equipment terminating at a "B" position at the called office, and there was connected directly to the multiple of the called station.

b. Local Tandem Trunks.

On a call completed via the local tandem board the subscriber's line was connected by the local operator to trunk equipment terminating in the tandem office. This tandem trunk was then connected to interoffice trunk equipment terminating at a "B" position at the called office, and there was connected directly to the multiple of the called station. If the called station was in a dial office, the calling subscriber's line was connected by the

FIG. 3

local operator to dial trunk equipment terminating on incoming selectors in a dial office in the called exchange and there through the local trunk to the particular dial office.

c. Straightforward Tandem Trunks and Toll Lines.

In the straightforward trunking the information necessary for completing the call is passed to the distant operator over the same conductors used for establishing the connection. On an originating call completed via the straightforward tandem trunk board the subscriber's line was connected by the local operator to the straightforward trunk equipment terminating at a position in the Los Angeles toll office. This trunk was then connected to a ringdown toll line terminating at an inward toll position at the called office, and there was connected to the called station.

Consideration Which Led to the Installation of the Dial Tandem System

The abnormal demands for telephone service between cities and communities have more than kept pace with the growth in population. The facilities at times have been taxed to the limit and a few years ago it became evident that new methods of handling the short-haul toll traffic must be devised. The toll board method is adequate for long distance toll traffic, but a faster

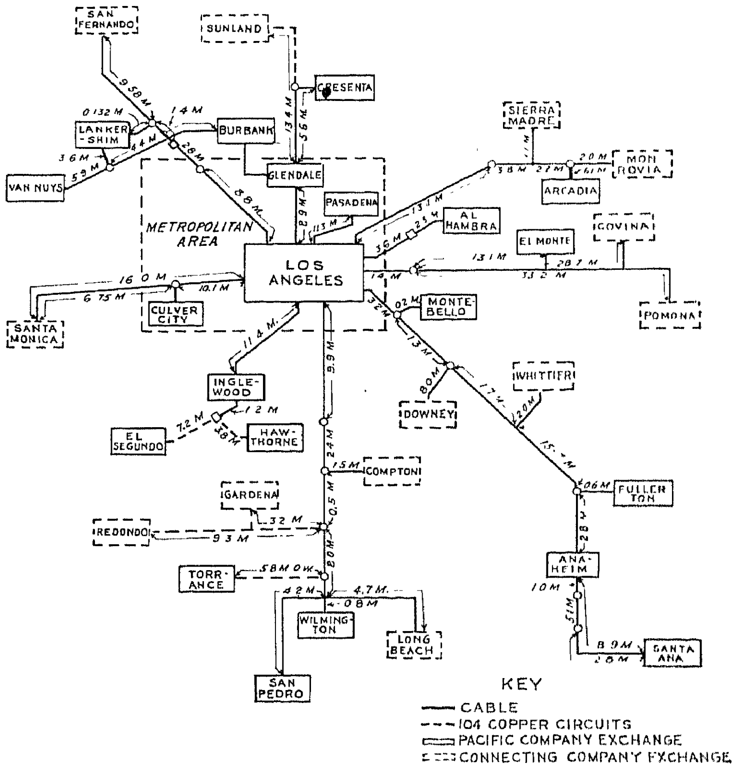

FIG. 4

method was required for moving the unprecedented increase in short-haul traffic.

The requirements for a more rapid and adequate method for handling the short-haul toll traffic have caused the telephone company to focus its efforts on furnishing short-haul toll service comparable to local service, and in 1923 a study was made of the application of tandem systems for handling the station-to-station traffic around Los Angeles. Step-by-step tandem and straightforward manual tandem systems were studied, both proving to be more economical and faster than the toll board method, the former being more economical than the latter. Decision to proceed with the Los Angeles tandem system project was made as soon as the results of the study were determined; and the engineering work for specific installations was started immediately.

In 1924, switchboard position equipment was placed in service in various Los Angeles central offices to care for the necessary manual services for dial stations which provided a practical means for handling short-haul toll calls originating from dial stations. In the same year

equipment was installed in all manual offices in order that dial stations could complete calls to manual stations in the same manner as calls to dial stations. This equipment is known as call indicator equipment and employs decimal switches and a bank of numbered lamps to record and display before an operator the number of the desired station. The operating features that these manual service positions and call indicator equipment provided, materially aided in reaching the decision to adopt the dial tandem system.

The Los Angeles dial tandem system was gradually placed in service, starting March 30, 1926. It is designed to handle all of the short-haul toll traffic included within a maximum radius of approximately 40 mi. from the tandem center as indicated in Fig. 3, except that which transmission and other considerations have prevented.

It was initially arranged to handle all the number service traffic between metropolitan area exchanges, Culver City, Los Angeles, Pasadena, Glendale, and the following outlying exchanges:

Alhambra	Fullerton	San Fernando
Anaheim	Gardena	San Pedro
Arcadia	Hawthorne	Santa Ana
Burbank	Inglewood	Santa Monica
Compton	Lankershim	Sierra Madre
Covina	Long Beach	Sunland
Crescenta	Monrovia	Torrance
Downey	Montebello	Van Nuys
El Monte	Pomona	Whittier
El Segundo	Redondo	Wilmington

The sizes of these areas in stations at the first of each year from 1925 to 1929, actual and estimated, are as follows:

Area	Actual			Estimated	
	1925	1926	1927	1928	1929
	Stations				
Metropolitan area:					
Four Exchanges	293,577	318,440	352,634	388,235	419,585
Outlying Area:					
Pacific Co. Exchanges	23,803	27,435	31,646	37,645	42,620
Connecting Co. Exchanges	51,206	55,315	62,646	70,635	79,120
Total	368,586	401,190	446,926	496,515	541,325

Fig. 4 indicates the routes and miles of cable and open-wire circuits between exchanges.

In June, 1927, the system was expanded to handle number service between exchanges within the metropolitan area, and in addition, to handle about 95 per cent of the number service between exchanges in the outlying area.

Under present conditions, the longest through connection practicable to establish over the tandem system is 55.7 mi. from office to office.

Description of the Tandem System

In general, the tandem system provides for a number of tandem trunks from the various offices in the tandem area terminating on first selectors of the step-by-step type located at the tandem center. Each level of the first selectors is wired to a group of second selectors on which are terminated completing trunks to the various offices served by the system. It will be noted that the use of first and second selectors will theoretically permit of reaching 100 different points, although practically this is somewhat limited because the first and zero levels of the first selectors are reserved for testing and special calls. As the system grows, third selectors can be introduced which will provide sufficient codes to care for the ultimate requirements. Two groups of first and second selectors are provided, one to handle calls from the outlying points to subscribers in Los Angeles, the other for calls from Los Angeles to subscribers in the outlying offices.

A subscriber in an outlying office desiring a Los Angeles number, see Fig. 5, will pass to his local operator the desired number as listed in the Los Angeles city directory. The local operator will then select an

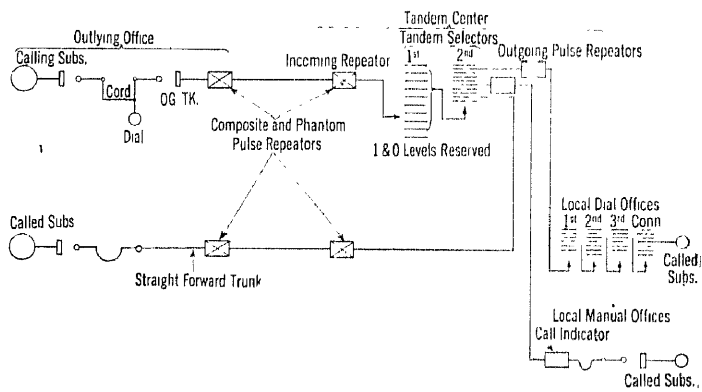

Fig. 5—Equipment Arrangement, Schematic Diagram

idle trunk to the tandem center and dial the number. If the call is to a dial system office, the first and second selectors at the tandem point will respond to the first two digits pulled by the operator to select the desired office. The remaining four or five digits, as the case may be, will be repeated on through the selectors and connectors at the terminating office to reach the proper called subscriber's line. If the called station is busy, a busy signal will be given to the originating operator. If the station is idle, the subscriber's bell will be rung automatically and upon the answer of the called party the supervisory cord lamp at the originating position will be extinguished as an indication to her that the called station has answered. The operation of the supervisory lamp by the called subscriber's switch hook provides the originating operator with complete supervision and a visual means for timing the call. After the completion of conversation, the calling and called parties will restore the receivers to the hooks, thereby causing the supervisory lamps on both cords to be lighted. The originating operator will then complete the timing, remove the answering cord from the

subscriber's jack and the calling cord from the trunk to the tandem system which will cause the automatic release of all switches involved in setting up the connection. If the call is to a manual office, see Fig. 5, the connection will be established in exactly the same way except that the desired number will be displayed on one of the call indicator positions in the terminating manual office. The call indicator operator will complete the call in the same manner as she would a local call. The supervision obtained by the originating operator is the same as that described above for a call to a dial system subscriber. On calls from a manual office in Los Angeles to one of the outlying points, the functions performed by the subscriber and the local operator will

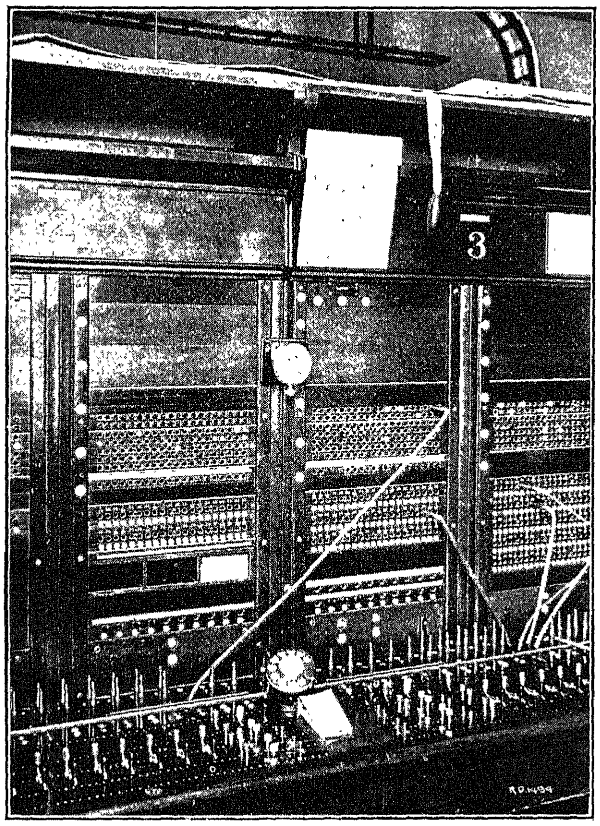

Fig. 6

be generally the same as that described above. On calls from a Los Angeles dial system office to an outlying office, the subscriber will first dial zero to reach his local operator after which the call will proceed in the same manner as described above for a call originating in a manual office. If the outlying point is a dial system office, the call will be completed in the same manner as described for a call from an outlying office to a dial system office in Los Angeles. If the call is for a manual outlying office, however, it will be completed by a straightforward operation; that is, the operator in Los Angeles will first dial the proper code to select a trunk to the desired outlying office. As soon as the trunk is seized, a signal will be displayed on the trunk before an incoming position. The incoming operator at the outlying office, upon answering the call, will automatically place a momentary tone on the connection which will indicate to the first operator that the incoming operator is ready to receive the desired number. The incoming operator, upon receiving the number, will complete the call to the desired

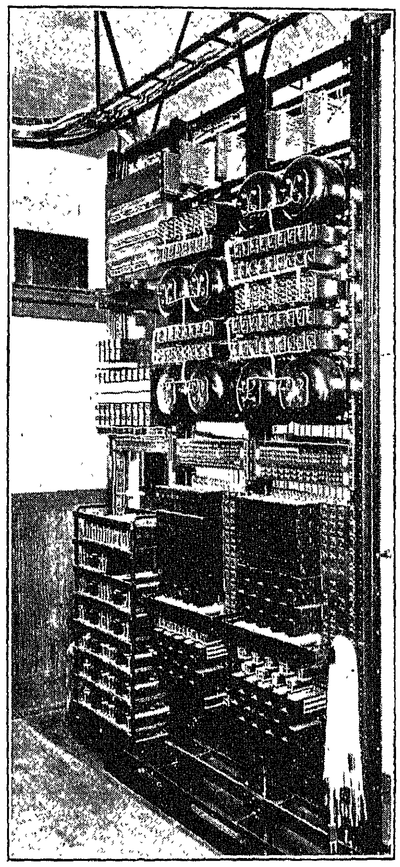

Fig. 7

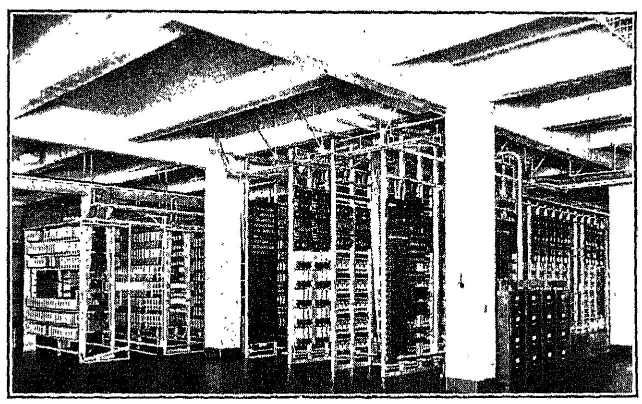

Fig. 8

subscriber by selecting the proper line jack in the manual switchboard multiple. As in the description of previous calls, the local operator in this case will also have complete supervision over both the calling and called subscribers.

The equipment required at an outlying office to

provide the above described operating features consists in providing a sufficient number of tandem and completing trunks with their associated terminal equipment to handle the peak load of the traffic. The operator's cord circuits are modified so that her position dial can be associated with any cord; or in cases where the volume of traffic is relatively small, a cheaper arrangement, consisting of the provision of a dial cord, would be installed. It would be well to mention here that no equipment of this nature was required for the Los Angeles manual offices. These switchboards had already been modified for dialing and for call indicator operation in order to provide a suitable method for completing calls to and from dial system offices in the local metropolitan exchange area. If these modifications had not been made, the economies of the machine switching in preference to manual straightforward tandem operation might be questionable. Figs. 6 and 7 show the local operator's switchboard equipment at the tandem office and 4000 selectors are required to do the switching.

The group of switches designated short-haul system performs the same functions as the group designated long-haul system except that it provides for the completion of calls to and from certain of the neighboring points to Los Angeles. The purpose of providing the so-called short-haul group is to permit of the use of small gage conductors on trunks which carry a relatively high volume of traffic between Los Angeles and outlying offices within approximately a 10-mi. radius. As an illustration of the economy of this arrangement, it would be necessary, if all calls to Pasadena were completed through a single group of tandem switches, to provide approximately 150 16-gage conductors in order that calls from Santa Ana, for example, would receive satisfactory transmission, although such calls are relatively few as compared with the total volume of traffic to Pasadena. By providing a separate group of selectors, known as the short-haul

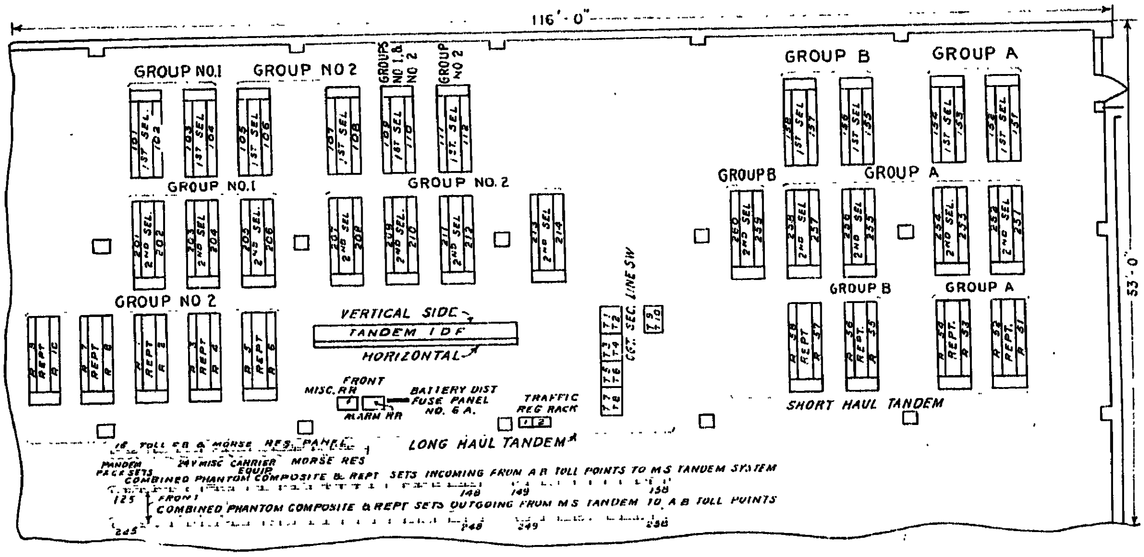

Fig. 9

and the tandem relay repeating equipment for seven outgoing and nine incoming phantomed trunks for the Hawthorne, California, office, which is typical of the outlying manual offices served by the tandem.

Fig. 8 gives a general view of the tandem equipment at Los Angeles. The floor plan layout of the equipment is shown in Fig. 9. On the left-hand side are the first and second selectors, pulse repeaters, distributing frame and outgoing secondary switches for completing calls to and from the more distant points; on the right-hand side the first and second selectors and pulse repeaters for completing calls to and from the nearby points are served by the tandem system. The first group, as noted on the sketch, is designated for convenience as the long-haul system and the second group as the short-haul system. These terms are merely equipment group designations and it should not be inferred that the two groups are provided for handling two types of traffic. A total of 2500 trunks terminates system, 20 conductors of 16 gage would be required on the long-haul system, whereas the remaining 130 trunks to Pasadena from the selectors of the short-haul system are of 19 gage and entirely satisfactory for the transmission requirements of the calls which it handles. The annual charges on 16-gage conductors per mile are approximately two times those for 19 gage.

A description of the selectors employed in the tandem system at Los Angeles is not required as they are of the well-known standard step-by-step type and are wired together in accordance with standard practises except that a cross-connecting frame is provided between selectors in order that the system will lend itself readily to expansion or other necessary rearrangement which may be brought about by future changes in traffic conditions.

The power for operating the various selectors, pulse repeaters, and out-trunk secondary switches is obtained from the power plant of a standard step-by-step dial

system central office located in the same building as the tandem equipment. At a number of the outlying offices it was necessary to add cells to the battery in order to raise the voltage to 48, which is required for the proper operation of the circuits.

The pulse repeaters which are used on both the in-

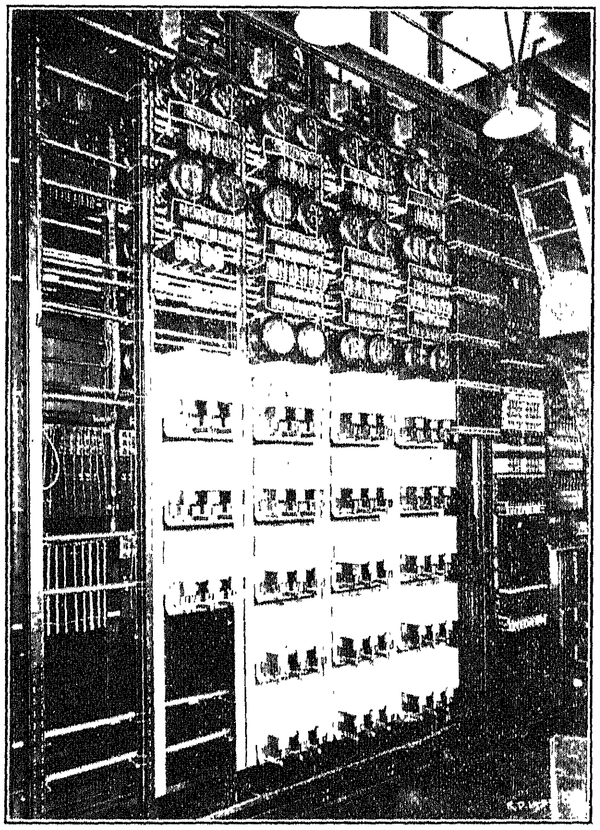

Fig. 10

coming and outgoing trunks from the tandem and outlying offices to repeat dial impulses from one section of the circuit to another are new both with respect to circuits and to the association of various pieces of apparatus required in circuits. Fig. 10 shows the typical layout of a pulse repeater frame for phantom trunks. The relays of the pulse repeater are mounted on a removable base and covered as a protection against dust in the same manner as standard equipment. The associated composite and repeating coils are shown mounted directly above the repeater relay equipment. It is the usual practise in engineering toll telephone equipment to mount the composite and repeating coils together with their associated condensers on separate frames and wire this apparatus to test jacks on the toll testboard. Such an arrangement will provide a rapid means for replacing defective apparatus which may have rendered an expensive toll line inoperative. It was decided in the engineering of this installation to forego some of this flexibility since the toll lines involved did not exceed approximately 40 mi. It was, therefore, practical to associate the composite and repeating coils on the same frames as the relays, an arrangement which effects considerable economy in floor space, mounting racks, and cabling, and also facilitates maintenance. The results of the operation of the tandem system with respect to maintenance, apparently justify our engineering decision in this respect.

In cases where large groups of trunks were required to handle traffic, such as between Long Beach and Los Angeles, considerable economy was effected by the use of outgoing trunk secondary switches. These switches perform the same function as the standard primary and secondary line switch arrangement employed in step-by-step dial system offices, the theory of which has been described in previous papers. Of course, in the case of the tandem system the economies are somewhat more marked, due to the fact that the trunks involved are considerably more expensive than the trunks which are saved by the use of secondary line switches in local step-by-step office practises.

Where phantom trunks are not used, the pulse repeaters are the same as those employed between local Los Angeles offices.

Referring now to the operating features of the principal circuits involved in completing a call through the tandem system, see Fig. 11 which illustrates a typical circuit at an outlying manual office used in a call to a Los Angeles dial system subscriber. Particular attention will be given to a description of the novel dialing and signaling arrangement for phantom trunks and to the pulse correcting device of the incoming pulse repeater circuit.

When a calling subscriber in an outlying office lifts

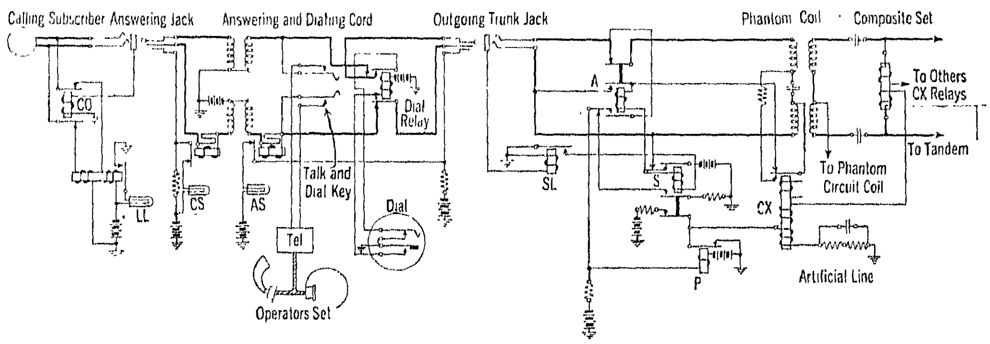

Fig. 11—Outlying Office Simplified Circuits

his receiver to originate a call, a circuit is closed from battery through the line relay on the contacts of the station switchhook. The resultant operation of the line relay closes a circuit to light the line lamp appearing before the operator who answers the call by inserting a plug of an answering cord into the subscriber's jack associated with the lighted line lamp. This closes a circuit by way of the sleeve of the answering cord to the cutoff relay in the line circuit, causing it to operate and disconnect the line relay from the subscriber's line, opening the lamp circuit, and extinguishing the line lamp. Battery is fed from the cord circuit repeating coil to the subscriber's set to energize his transmitter, and the calling supervisory lamp is under the control of the station switchhook.

The operator then obtains the desired number from the calling subscriber and if the number is in a local dial system office in Los Angeles she will select an idle

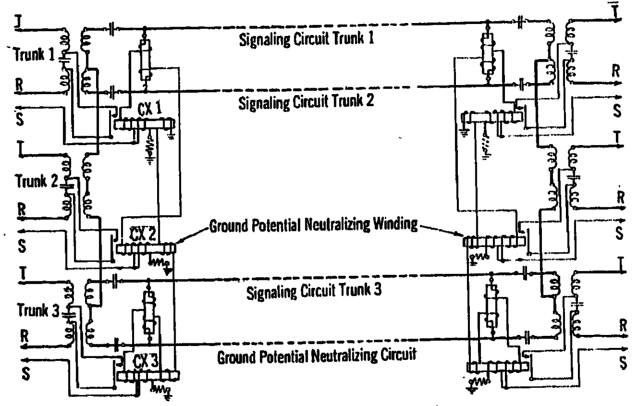

FIG. 12—PHANTOM TRUNK GROUP

Composite sets and phantom coils. Relays compensated for ground potential difference, simplified circuit.

trunk to the Los Angeles tandem office and insert therein the other end of the cord which she has used to answer the calling subscriber. Plugging into the outgoing trunk jack closes the circuit of the sleeve relay in the trunk to battery on the sleeve of the calling cord. The resultant operation of the sleeve relay, designated *S L* on the sketch, closes a circuit from ground through the winding of the *S* relay to battery on the ring conductor of the trunk. Relay *S* operates and locks on its own front contact, closing a circuit to operate the *P* relay and apply battery to the midpoint of the differential winding of the *C X* relay. Relay *S* also applies battery to the winding of the *A* relay which does not operate at this time.

The operator in dialing pulls the dial off normal, closing its off-normal contacts and operating the dial relay to associate the dial with the calling cord. The operation of this relay disconnects the repeating coil from that end of the cord and connects ground through the pulsing contacts of the dial to the tip conductor and ground through the off-normal contacts to the ring conductor of the cord. This latter application provides an operating ground for the *A* relay in the trunk, whose principal function is to connect the *P* relay to the tip conductor so as to prepare it to receive the pulses from the dial. The *P* relay repeats the pulses to a relay, corresponding to the *C X* relay of the trunk, in the incoming repeater at the tandem center, at the same time not affecting the *C X* relay in the trunk, which is used to receive a signal upon the answer of the called party and so extinguish the lighted supervisory lamp in the calling cord.

This two-way signaling feature, *i. e.*, pulsing in one direction and supervising in the other, over a single wire, is accomplished by an application to telephone signaling circuits of the familiar duplex principle of telegraphy. This application makes possible the use of phantomed trunks from the outlying points to the tandem center with accompanying economies in outside plant.

These trunks, as shown in Fig. 12, are provided with phantom coils and simplified composite sets, through which the four metallic leads of the phantom group are brought out to duplex relays. All of this apparatus is interposed on these trunks between the regular outdialing trunks, already described, and the incoming pulse repeaters at the tandem center.

Referring to the diagram, the action of an out-trunk circuit when picked up by an operator is to furnish battery instead of ground to the lead designated *S* on the particular channel selected. The resultant battery flow passes to the midpoint of the differential winding of the duplex relay and there divides in equal parts, one part passing by way of one-half of the differential winding over the line to the distant relay at the tandem center and the other part passing through the other winding and through an artificial network of electrical characteristics similar to the line attached to the other winding. These two current flows, being equal in strength, produce equal magnetomotive forces opposite in direction which have no effect upon the relay. That part of the current, however, which has passed over the line flows through the two windings of the distant duplex relay to ground through its associated artificial line and through the two windings of the relay in an aiding direction, operating this relay to actuate the repeater circuit and so pick up an incoming selector. Pulses from the operator's dial, therefore, will control this distant duplex relay, which in turn sets up the connection through the tandem system in the usual way.

On the answer of the called party, the incoming pulse repeater furnishes battery instead of ground to the lead designated *S*, which flows in opposite directions through the duplex relay windings, one part through the artificial line and the other over the line, through the two windings of the duplex relay at the outlying point. The operation of this relay retires the operator's supervisory lamp in the calling cord, indicating to her that the called party has answered.

At the completion of conversation, the hang-up of the called station causes the incoming selector to remove battery from the duplex circuit, releasing the CX relay which lights the supervisory lamp associated with the calling cord as a disconnect signal. The disconnect of the operator removes the battery from the lead S, thereby releasing the distant duplex relay, which in turn releases the switch train.

A similar operation takes place when the phantom channel, designated "Trunk 2," in Fig. 12, is selected by an operator. The signaling, however, is done over the second wire of the first metallic pair. For the other side circuit, designated "Trunk 3," the signaling is done over one of the wires of the other metallic pair. This, it will be observed, utilizes but three wires of the four in the phantom group, allowing the use of the fourth to overcome any effect on the signaling relays which might be occasioned by current flow due to adverse ground potentials. This is accomplished by adding to each of the duplex relays a third winding, all connected in series by means of the fourth lead. Any ground potential difference between the two ends of the circuit

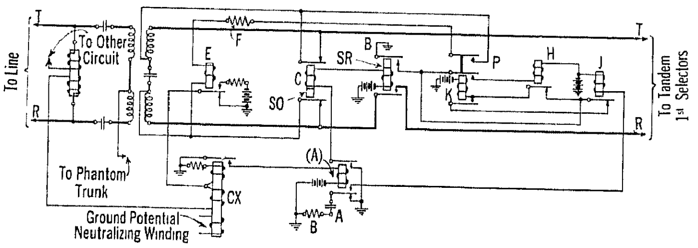

Fig. 13—Incoming Pulse Repeater

With pulse corrector simplified circuit

which might cause current to flow through the differential windings of the duplex relays will be neutralized in effect by a similar current flowing through the compensating windings over the fourth wire.

The incoming pulse repeaters into which the duplex-composite circuits work have embodied in them a means for correcting for the distortion of dial pulses due to line characteristics. The use of this feature in the incoming repeaters makes it feasible to provide reliable service over longer trunks than has heretofore been practicable and so embrace in the system as many towns within the wide range of the tandem area as are economically warranted.

When the trunk is selected by an operator at an outlying point, the CX relay of the incoming repeater at the tandem center shown in Fig. 13 is energized, as has been explained. This relay operates the A relay of the incoming repeater directly on its front contact, closing a circuit to operate a "slow operate" relay C and a "slow release" relay B in series. The latter relay closes a circuit to operate the K relay which locks, operated on its own front contact through a back contact of the J relay. The K relay also closes a circuit to operate the H relay which opens the original operating circuit of the K relay and closes on the contacts designated P, a bridge across the inside terminals of the repeating coil consisting of resistance F and relay E in series.

Current from the first selector of the tandem train flows through this bridge operating the A relay of the first selector in the usual way. Relay E is not affected by this current flow since it is polarized to operate on a current in the reverse direction.

At the first pulse from the operator's dial at the outlying point, the circuit operating the CX relay is opened, causing the release of that relay. The A relay in turn is released, opening the circuit through the C and B relays. The former releases, and being slow to operate, remains released during the train of pulses following, while the latter, being slow to release, remains operated during this time. On its other back contact, the relay A grounds the condenser A through the resistance B.

On the opening of the circuit at the first pulse, nothing occurs in the repeater to affect the condition of the associated first selector. On the closure of the circuit at the end of the first pulse, a pulse of measured length is sent to operate the first selector as follows:

The operation of the CX relay closes the circuit to the A relay which connects the discharged condenser A to battery through the winding of relay J. On the short surge of charging current the relay J momentarily operates, opening the locking circuit of the K relay, causing it to release, and open the contacts designated P to start the first pulse to the selector. The release of the K relay also opens the circuit to the winding of the H relay which, when released, establishes the original operating circuit of the K relay, which operates to close the P contacts completing the pulse and to lock through the now restored back contact of the J relay.

The length of the pulse to the first selector is determined by the release and operate time of the H and K relays, respectively, thus correcting for any distortion of dial pulses due to line characteristic.

Succeeding pulses of the first digit and following digits are repeated in like manner to the selectors of the tandem train of switches, and through an outgoing trunk repeater to the switch train of the local office, to select in the manner well known in step-by-step practise, the terminal of the called line.

Upon the answer of the called subscriber, the battery flow from the tandem switch train to the incoming repeater is reversed, operating the polarized relay E. The midpoint of the differential winding of the CX relay is thereby changed from ground to battery, causing, as previously outlined, the operation of the CX relay in the outgoing trunk at the outlying office and the subsequent extinguishing of the calling supervisory lamp.

At the completion of conversation the current flow through the E relay again reverses, causing the release

of the relay and lighting of the distant supervisory lamp as a disconnect signal. The disconnection by the operator releases the $C\,X$ and A relays, opening the circuit to release the B and K relays. The opening of contact P of the K relay restores the switches of the tandem train.

Where the trunks outgoing from the tandem office terminate in local manual offices equipped with call indicator completing positions, a pulse repeater is provided to repeat the decimal pulses directly to the call indicator display apparatus. This apparatus is substantially the same as that in use in panel dial system offices which has been described in early papers on the panel system[2].

Trunks outgoing to manual offices not equipped with call indicator are operated by what is known as the straightforward trunking method. This method embraces most of the offices in the outlying towns which connect to the tandem system, and a simplified diagram of one of the types of trunk circuits is shown on Fig. 14.

When the trunk is selected at the tandem point, the outgoing repeater sends battery over one of the wires of the phantom trunk group, in a manner similar to that already described for the outgoing trunks, to cause

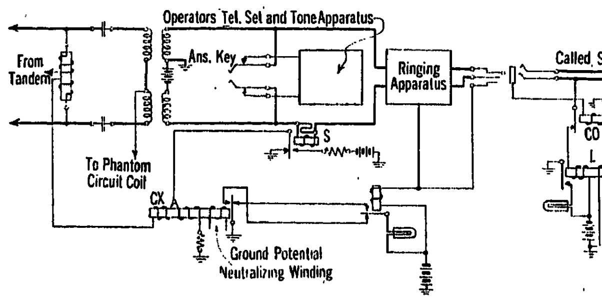

FIG. 14—COMPLETE TRUNK, SIMPLIFIED CIRCUIT

the relay $C\,X$ to operate, lighting the guard lamp through a chain of relays to appraise the operator of a waiting incoming call. The operator answers by operating the talking key on the completing trunk, bringing into play apparatus in her telephone circuit which sends a momentary tone to the calling operator, to advise her that the completing operator is ready to receive the call. She then plugs the completing cord into the multiple jack of the line desired.

The sleeve circuits of the cord and line are closed, operating the cut-off relay in the line to remove the associated line relay and setting in operation the machine ringing apparatus in the cord.

When the called subscriber answers, machine ringing is tripped and the circuit closed through to the repeating coil in the cord. Battery through the repeating coil flows over the line to energize the station transmitter and operates the series supervisory relay S. This relay in operating places battery on the midpoint of the differential winding of the $C\,X$ relay, causing the $C\,X$ relay in the outgoing repeater to operate, and by means of a reversing relay, reverse the battery flow through the tandem switch train to the incoming repeater. As already described, this results in retiring the calling supervisory lamp at the originating office.

At the completion of conversation the hang-up of the calling party lights the calling supervisory lamp as a disconnect signal and the called party's hang-up lights the other supervisory lamp. The disconnect of the originating operator releases the tandem switch train, in turn releasing the outgoing trunk and lighting the disconnect lamp through the back contact of the now restored $C\,X$ relay at the completing position.

PLACING THE TANDEM SYSTEM IN OPERATION

With the introduction of the dial tandem service came many interesting problems. As in most cases where communities are joined together by new communication methods, the various interests and general viewpoints of those concerned present an interesting and difficult problem to solve on a mutually satisfactory and equitable basis. The area includes 12 connecting companies which were using five different makes of equipment. The two larger of these included one exchange of 28,000 stations and another of more than 13,000 stations, both of which originated a large amount of toll traffic in proportion to their size. In addition to providing new equipment and rearranging existing equipment at the outlying points, it was necessary to instruct the local operating force at each place in the proper operation and maintenance of their equipment in order to obtain the desired service results.

In order to acquaint the operators with the tandem system, a number of bulletin cards with the names and codes of offices was prepared and placed on each position handling tandem calls. Information and instructions as to whether the tandem code together with the subscriber's number or only the code should be dialed in passing the order to the completing operator, also were included. The accompanying table shows one of these bulletins. Very little educational work was required in the training of the operators in Los Angeles as they were already accustomed to dialing. The straightforward completing feature of the tandem system was quite like the manual straightforward tandem system already in operation. Considerable training was done in the outlying offices, however, as many of the operators were not accustomed to dialing and in some cases were not familiar with the requirements in the proper handling of short-haul toll traffic. A brief description of the tandem method of operation was prepared for each outlying town, which was discussed with the supervisory officials who presented the problem to their forces. The questions and answers presented in these conferences resulted in a knowledge of the system as well as the details of the operators' work being known to the operating forces before service was started. In establishing the many routes which were made effective with the opening of the tandem system, it was essential that

2. Paper by Craft, Morehouse, and Charlesworth, A. I. E. E. TRANS. Vol. XLII, 1923, p. 187.

Complete by name or number				Complete by number
Fire Department	FItzroy 3131	Without charge		Without charge
Emergency Hospital, Receiving Hospital	FAber 1441	Information	113	FAber 9000 to FAber 9999
Police Department	MEtropolitan 6100	Repair Clerk	114	All Offices 0000 to 0009
Sheriff's Office	TRinity 9111	Wire Chief	117	
		U. S. Long Distance	118	
		Pacific Long Distance	110	
		Pacific Telegraph	FAber 9045	
		Telephone Company	FAber 9060	

NUMBER SERVICE INFORMATION

Name	Abr.	Route-Code	Initial Rate	Name	Abr.	Route-Code	Initial Rate
Alhambra	Alh	I H-21	10c	Long Beach	L Bch	LH-52*	20c
Anaheim	Anhm	LH-42	25c	Moneta		LH-25-Gard	10c
Arcadia		A-B-T	15c	Monrovia	Mon	A-B T	15c
Brea		2 #		Montebello	Mont	LH-37	10c
Burbank	Brb	LH-32	10c	Newhall		2 #	
Chino		2 #		Niagara	Nig	Stf (Col)	10c
Claremont	Clmt	2 #	25c	Orange	Org	2 #	
Colorado	Col	Stf	10c	Owensmouth	Omth	A-B T	20c
Compton	Comp	LH-30	10c	Placentia	Plac	2 #	
Covina	Cov	A-BT	20c	Pomona	Pma	2 #	
Crescenta	Crsn	LH-46	10c	Redondo	Rdn	A-B T	15c
Culver City	Clv	A-BT	10c	San Dimas	S Dms	2 #	
Downey	Dny	2 #		San Fernando	S Fdo	A-B T	20c
Duarte		A-BT-Mon	15c	San Gabriel		LH-21	10c
El Monte	El-Mt	LH-23	10c	San Pedro	S P	LH-41	20c
El Segundo	El Sg	LH-24	15c	Santa Ana	S Ana	LH-44	25c
Fair Oaks	Fo	Stf (Col)	10c	Santa Monica	S Mon	LH-53*	15c
Fullerton	Ful	LH-43	20c	Sierra-Madre	S Mdr	A-B T	15c
Gardena	Gard	LH-25	10c	Sterling	Stg	Stf (Col)	10c
Garden Grove		2 #		Sunland		A-B T	15c
Glendale	Gln	C.C.	10c	Terrace	Ter	Stf (Col)	10c
Hawthorne	Hthn	LH-47	10c	Torrance	Tnce	A-B T	15c
Huntington Bch	HtBch	2 #		Tustun		2 #	
Hynes		2 #		Van Nuys	V Nys	LH-39	15c
Inglewood	Ingl	A-B T	10c	Wakefield	Wak	Stf (Col)	10c
Lankershim	Lank	LH-36	10c	Whittier	Whtr	LH-54*	15c
La Verne	La V	2 #		Wilmington	Wlmg	LH-45	20c
Lomita	Lta	2 #					

*To these points the subscriber's number must be dialed in addition to the code

On Calls by Name to Offices Underlined in Red Advise the Calling Party that the Call Should be Given to U. S. L. D.

On Calls by Name to Offices in Red Advise the Calling Party that Particular Person Calls are not Accepted

On calls by name to offices in black connect the calling party with long distance

Computed Charges											
Initial rate	5.1 to 6 min.	6.1 to 7 min.	7.1 to 8 min.	8.1 to 9 min.	9.1 to 10 min.	10.1 to 11 min.	11.1 to 12 min.	12.1 to 13 min.	13.1 to 14 min.	14.1 to 15 min.	Overtime rate
10c for 5 min.	15c	15c	15c	20c	20c	20c	25c	25c	25c		5c for ea. 3 min.
15c " 5 "	20c	20c	25c	25c	30c	30c	35c	35c	40c	40c	5c " " 2 "
20c " 5 "	25c	25c	30c	30c	35c	35c	40c	40c	45c	45c	5c " " 2 "
25c " 5 "	30c	35c	40c	45c	50c	55c	60c	65c	70c	75c	5c " " 1 "

means be provided so that customers might easily obtain telephone numbers in other exchanges and the necessary routines were established to accomplish this.

A series of tests of equipment was made at the outlying offices where limits were severe. These tests included dialing and signaling from minimum to maximum limits with respect to line leakage and line balance resistance, relay adjustments, and voltage variation. The amount of cross-talk and audible interference from dialing and signaling was determined. On open-wire routes, particular attention was directed to line leakage and balance of composite sets located at the cable junction. When placed in service, each cut-over operation was limited to trunks in one direction only and, as far as possible, but one office was brought in at a time. Thus, the change from the toll board to the dial tandem method was carried out in an orderly manner with the least possible confusion to and reaction on service.

In some cases, a few trunks only were placed in operating condition several days before actual service was established over the route in order to give the operators preliminary training during their regular work. Maintenance routines and practises were issued sufficiently in advance of the cut-over so that practically no difficulties were experienced in equipment failures. Very close cooperation was necessary between the equipment and traffic engineers and the cut-over field forces of the Traffic and Plant Maintenance Departments. The schedule of cuts was thoroughly coordinated and the people who were finally charged with the responsibility of operating and maintaining the system were well trained.

It was originally planned to cut-over all the offices involved during May, 1926, and in addition, to introduce number service to other points within a 40-mi. radius of Los Angeles. With the completion of the

installation at the tandem office in March, it was found possible to start service earlier to most of the offices handling a comparatively large volume of the traffic. A sequence cut, therefore, was planned which would permit the tandem system to carry the traffic gradually, avoiding any too abrupt change in operation or labor requirements in the various offices. The actual cut-over of the initial equipment comprised a period of nearly two months. Following this, other exchanges have been given the service from time to time, temporary equipment being replaced with permanent, so that there now remain only six points originally planned for the tandem system that are not actually receiving its full benefit. These exchanges are Arcadia, Covina, Pomona, Redondo, Sunland, and Torrance. The most recent cut-over of magnitude in this connection was in June, 1927, when Pasadena was changed from manual to dial operation. At this time a tandem center was established serving Pasadena exchange with direct connections to four Los Angeles offices and to the following outlying exchanges: Alhambra, Arcadia, Crescenta, Glendale, Monrovia, and Sierra Madre.

Discussion

ADVANCE PLANNING OF THE TELEPHONE TOLL PLANT IN LONG-DISTANCE COMMUNICATION

(Chamberlin)

TANDEM SYSTEM OF HANDLING TOLL CALLS IN AND ABOUT LOS ANGELES

(Jacobsen and Wheelock)

Del Monte, Cal., September 14, 1927

M. R. Sullivan: Speaking as a telephone traffic engineer, I should like to endorse what Mr. Chamberlin has said with respect to the traffic features involved in advance planning of telephone toll plants.

Traffic in the telephone industry takes the form of telephone calls or messages and since the plant is provided for the purpose of transmitting messages, the traffic features—the volume of traffic, the character of the traffic, the routing of the traffic, and the manner of handling of the traffic—are of controlling importance in the determination of the size and type and arrangement of the plant to be provided.

Mr. Chamberlin has outlined the important function of the commercial surveys in forecasting telephone developments with respect to growth in the number of telephones and their distribution by area, and by classes of telephone service.

Of equal importance are the forecasts of telephone calls per telephone. Telephone usage per telephone—particularly toll usage—does not remain constant year by year, but varies with business activities, and is subject to other influences, so that in the advance planning of the telephone toll plant it is necessary to give very careful study to the trend in the usage per telephone.

During the past few years, and especially during the last one or two years, there has been a marked trend upward in the toll usage per telephone. Many influences, no doubt, have played a part in this greater usage of the service. A feature of outstanding importance in this increase in toll usage lies, undoubtedly, in the results secured through various improvements which have been made in the toll service. For example, transmission within the last few years has been materially improved. It is easier to carry on intelligible conversation over the circuits, and that, of course, has had an effect upon the amount of toll business offered. In addition, the speed of handling the calls, and the convenience with which the call can be placed, has materially improved.

Up to a year or so ago, for a long-distance call, the calling party had to give details of the call to the long-distance operator, hang up the receiver, and later be called back when the connection was ready, or when a report on the call was obtained. This manner of handling a toll call required five or six minutes.

Today by giving the number desired to the long-distance operator, the chances are about nine to ten that the call will be completed immediately and without the necessity of even hanging up the receiver. The convenience of placing calls and the improved speed which this change has brought about has an effect in stimulating the number of toll calls offered.

Another recent change of considerable importance in the handling of toll calls is the proportion of calls handled by the "exchange operator." When I say exchange operator I refer to those completing connections from one telephone to another in the same exchange. The easiest way of placing a toll call is for the party calling simply to give the number of the desired call to the exchange operator, in the same manner as for a local connection. This method also produces the fastest service. For many years, large numbers of the toll calls have been handled by this method but of recent years there have been developments which greatly extended the range to which this most desirable of operating methods can be applied.

One of the developments is the improved tandem system of routing toll calls, which Mr. Wheelock has described. The result is that today a very much larger proportion of the toll calls is handled by this method. Take the exchange of Monterey; something like 48 per cent of all the toll calls originating at this exchange are handled by the exchange operator; whereas two or three years ago none of the toll calls was so handled. This improved method, therefore, has had application not only at the large metropolitan exchanges but also at the small exchanges.

I think it might be said that, like the automobile industry, the telephone toll business is constantly producing a bigger and better service; and in the advance planning of the toll plant, it is necessary to foresee the further improvements which will be made in the toll service and the effect these improvements will have on the volume of toll business offered and the size of the plant required.

R. C. Barton: Mr. Chamberlin's paper makes clear certain high lights of technic of the telephone business, and why universal and uniform telephone service is a natural objective.

As he has pointed out the value of the service to those who have it is increased by each addition to the system. Universal service, therefore, becomes a strong objective. He has indicated that the service must satisfy the party called as well as the calling party, so that service from the customer's viewpoint is demanded, and that calls for uniformity and standardization.

The paper brings out three important and distinctive characteristics of the telephone plant. One is that there is a very great multiplicity of lines and associated apparatus; another, that each line must be electrically smooth and stable in its operation; and the third, that the character of the telephone plant is continuously and rapidly changing.

In regard to this great multiplicity of lines exclusive use of the lines between parties is, to some extent, obviated in the toll-plant through the use of phantom circuits and carrier channels; however, Mr. Chamberlin's description of the San Francisco-Sacramento toll cable shows that multiplicity of lines is a strong characteristic of the telephone plant. This is more pronounced in the exchanges where the lines provided in one office district may be of the order of 100,000 and the conductor footage of the order of hundreds of millions.

Stability and smoothness are required in the electrical characteristics of the lines because of the complicated wave pattern which must be faithfully transmitted. The effect of rapid change

may be appreciated by considering the condition produced when it becomes necessary to throw all the wires on a 50- or 60-wire toll line into cable.

These distinctive characteristics of the plant and of the service are largely responsible for the special engineering, construction and maintenance practises which are followed in the telephone art. One of the practises which receives very special emphasis has been made the key-note of Mr. Chamberlin's paper. It touches those activities which have to do with the study of the field of operations with respect to potential telephone development and the preparation of well matured plans, looking far to the future, to serve as a guide in the orderly placing of the plant.

Now the nature of the problem also requires another kind of advance preparation which takes the form of engineering, construction and maintenance handbooks. These are prepared to relieve the engineers of much of the work they would have if each job were designed from the ground up at the time it was being planned. These handbooks also insure the orderly placing of the plant in accordance with practises which have received nation-wide study and application.

It may be of interest to indicate something of the extremes to which it is desirable to go in such activities.

As one illustration, The Pacific System maintains a supply catalog which is available to all interested employees, and this catalog lists all materials, tools, and apparatus used in the conduct of their work. It is profusely illustrated and comprises about 500 letter-size pages. Among the items listed in this catalog are the handbooks previously mentioned. There are 75 of these devoted to the subject of construction methods alone, and some 100 supplementary leaflets affecting these. The construction methods handbooks cover such subjects as pole-line placing, underground conduit construction, guying, aerial-cable placing, etc. To the subject of aerial-cable placing alone, 120 handbook pages are devoted. These are well illustrated, and this book is typical of the others. Illustrative of the engineering handbooks is one on pole-line design. With this book, the engineer may quickly and easily determine the class of pole to select for any set of conditions, such as service value of the line, wire and cable load, temperature, wind and sleet conditions, span length, etc. Illustrative of the maintenance handbooks is one devoted to pole-line replacement and reinforcement inspection. This handbook prescribes the methods to be used in making inspections and includes tables of minimum ground-line circumference below which poles under the various conditions of load, service value, etc., are not permitted to go.

I should like to endorse Mr. Chamberlin's remarks regarding the value of cost-comparison studies in engineering, and the value to the student engineer of a fundamental knowledge of the procedure in such studies.

Making cost comparisons is a measurement process in which the principal unit is the dollar. One of the great physicists—Lord Kelvin, I believe—has written: "When you can measure what you are talking about, you know something about it; and when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind."

The rules of the mathematics employed when relating the various quantities developed in a measuring process require all quantities to be expressed in like units. For example, in a space measurement, units of length may arise as inches, feet, and yards, and require all to be expressed as feet by the application of suitable conversion factors. Likewise, in measurements where the dollar is the unit, it is required that before quantities of money may be properly compared, they must be operated upon by suitable conversion factors which will reduce all expenditures and investments such as first costs, present values, periodic payments, future recoveries, and the like, to a common time basis. The laws governing the set-up of the postulates and the facts in this sort of problem, and the method of solution, constitute the fundamentals of cost analysis, and it is these fundamentals which I agree with Mr. Chamberlin should be given some prominence during the college course. This is not done now.

Bancroft Gherardi: I was particularly interested in the remarks about inductive coordination, for, in the last five or six years, I have been the representative of the Bell system, working with R. F. Peck, the representative of the National Electric Light Association on the Joint Engineering Subcommittee, to solve our problems of inductive coordination; and before we had gone very far into that work, we came to the conclusion that 10 per cent of our problem was technical and 90 per cent was to bring about between the people on both sides of the question, a friendly and cooperative approach to that question.

It is evident that here, as in other parts of the United States, the problem is generally being approached cooperatively, and thus we are able to find mutually satisfactory solutions.

N. B. Hinson: Mr. Gherardi has called attention to the fact that there are certain classes of work that can hardly be classed as electrical engineering being done by the telephone companies. Mr. Chamberlin in his paper has emphasized this fact, and the same thing is true of the power system where there are certain elements of planning which are not electrical at all.

The telephone companies were the pioneers in the making of development surveys and population studies which could be used in advanced planning. A number of the power companies are falling in line with the same idea and finding population surveys in rapidly growing territory, like southern California, very useful, especially where yearly increases as high as 15 and 20 per cent occur.

J. E. Heller: (communicated after adjournment) Mr. Chamberlin has pointed out that the advance planning of telephone toll plant requires the coordinated effort of several departments, who, in turn, require specialists to solve the problems requiring their participation in the project.

As indicated in the paper, open-wire carrier-current systems and cable conductors may be used to provide long-distance communication circuits. The use of a given type of facility requires the determination of electrical as well as economic factors. After making allowance for the transmision losses of the trunking and local loop plant used at each terminal, it is electrically possible at the present time to talk with various facilities over the distances given below:

Type of Facility	Mi.
104 Open-wire	5000
165 Open-wire	6700
19-Gage 2-wire cable circuits	700
16-Gage 2-wire cable circuits	1200
19-Gage 4-wire cable circuits	1500

Since a given circuit may be used as a link in a long built-up connection, consideration must be given to the number of links involved and each link designed so that it may be connected to any other link in the system. This requires that individual links must be somewhat shorter than indicated previously. The overall length for a given grade of transmission will also be affected by the amount of transmission loss allowed in the terminating trunks and loops. Undoubtedly future developments will materially extend the length over which it is practicable to talk with the present types of conductors.

Usually several plans are considered when a large addition to a plant, such as a toll cable, is indicated. Preliminary studies require an approximate electrical design of the circuits for each plan together with the cost of providing the facilities for a long period of years. The preliminary studies together with other basic data as presented by Mr. Chamberlin determine the plan to be adopted. After a particular plan has been adopted it is

necessary to review the electrical design in order to determine the loading arrangement of the conductors, the location of repeater stations, and the equipments to be placed at each station from year to year.

Carrier-current systems are being used extensively in the provision of additional facilities. The increase in facilities possible on a given lead by this means has been indicated in the paper. Before a number of systems can be operated on a lead it is necessary to rearrange the wires by transposition to reduce the interference between systems. The present standard arrangement makes use of alternate crossarms. While, in general, the costs are such as to make the use of adjacent crossarms for multi-channel carrier-telephone operation undesirable, in special cases, the added expense may be justified by other considerations.

The single-channel system developed for use on short hauls may be placed on the flat phantom groups of adjacent crossarms since the interference between systems of this type is less than that between multi-channel systems which occupy a higher frequency range.

A Carrier-Current Pilot System
of Transmission Line Protection

A. S. FITZGERALD[1]

Introduction

THE increasing complexity of modern transmission networks presents many difficult problems in connection with the design and application of protective relays.

On the larger systems, the use of increased time delay may be inadmissible on account of the difficulties met with in maintaining stable operation. Rather, there is a tendency in the direction of reduction in the time of operation of relays.

Thus, there is a growing interest in differential methods of protection; that is, in systems in which comparison is made between currents which under normal conditions are necessarily equivalent. These have the advantage of not being dependent upon the performance of relays in other circuits for their selective action.

The simplest form of differential protective arrangement consists of a circuit embracing a portion of a power system (such as a generator winding or transmission line), and registering any difference which may occur between the current entering or leaving the section protected.

Such arrangements offer very definite advantages over all other selective relay schemes, in that each section of the network so protected is a unit in itself and it is not affected by any other protective measure, nor by any alterations in the network arrangement. Thus no changes in the relay setting are necessary nor are these, in general, influenced by the direction of flow of power or fault current, nor by the settings of relays on connecting lines, as is the case with time delay overload protection. Moreover, in differential systems, faults may be cleared with a minimum loss of time.

These advantages are so marked that the differential system of protection is employed almost universally for the protection of generator windings, and similar applications where the extent of the circuit protected is a matter of yards rather than miles. For the protection of lines, however, the cost of the special pilot conductors has greatly restricted the application of this type of relay system, and it is not in general use in this country except for short distances or where there are so many sections in series that time delay methods are not desirable.

The success that has attended the use of differential pilot wire schemes in other countries, where the length of lines is less, indicates the desirability of a means of furnishing a similar service without the necessity of special conductors.

Carrier Currents

The term carrier current is employed as descriptive of a-c. energy generated at frequencies which lie, roughly, between 10 and 200 kilocycles. At these frequencies, the transmission of electrical energy exhibits special characteristics due to which it is possible to superpose carrier-current-control circuits on transmission lines or cables.

Carrier current is conducted more or less freely by straight conductors, and is restricted thereto by breaks or open circuits, except in so far as capacity paths are provided by parallel lines situated in close proximity. Carrier current may be employed for control systems because circuits may be provided which will conduct the carrier current but which will not effectively pass 60-cycle power current, and by means of which the carrier current may be introduced into, or taken out of, a power system.

Conversely, the flow of carrier current can be restricted within certain specified limits by circuits which provide a high impedance to carrier current but do not affect power currents.

Carrier current energy is commonly generated by means of three-electrode tube oscillators.

Requirements of a Protective System

A protective scheme suitable for association with carrier current operation and desirable from commercial and operating aspects, will preferably include the following features:

1. Radio Engineering Dept., General Electric Co.

Presented at the Pacific Coast Convention of the A. I. E. E., Del Monte, Calif., September 13-16, 1927,

1. The employment of potential transformers will be avoided.

2. The scheme should not require any definitely quantitative function on the part of the carrier apparatus since there may be variations in attenuation.

3. There should be no apparatus installed as part of the protective system which in itself represents an extension of the liability to trouble of the circuit protected. Current transformers of high safety factor, preferably of the bushing type, should be used. The carrier-current coupling equipment should be of the most reliable form available.

4. The equipment so far as possible, should be entirely current operated; that is, its operating power should be derived directly from the fault current.

5. Failure of the carrier-current apparatus should not render it possible for a fault to remain on the line thus disturbing the whole power system. Rather such a defect should advertise its presence by causing only the individual line to trip unnecessarily if overloaded.

6. The system should be suitable without modification for installation at any point in a network irrespective of possible direction of flow of fault current, etc.

7. It should be possible to check the carrier-current equipment at any time without interfering with service.

8. In view of the fact that a restricted range of frequency is assigned to control systems, only one frequency per line protected should be used.

General Principles

In its simplest form, differential protection consists of the installation of two current transformers at each extremity of the circuit embraced, one to receive the current entering the section, and the other, that leaving it. The secondaries are either connected in opposition and in series with one or more relays; or more usually connection is made so that the currents normally circulate, in which case the relays are connected across equipotential points. In either arrangement, the relays, normally, should receive no current, but on the occurrence of a fault, which will be a difference between the entering and leaving currents, a corresponding difference will appear in the relays. Numerous refinements and variations of this principle have been evolved in order to overcome difficulties in balancing and to render the apparatus immune from tripping on heavy "through" currents.

It will be perceived that the function of the pilot conductors is to furnish one end of the line with a sample of the current at the other end, in order to provide the relays with means of discriminating between sound and faulty conditions.

It is not, however, desirable to employ exactly similar principles when carrier current is to be used in place of a pilot line. This is due to the fact that carrier current is usually transmitted by means of resonant circuits. Because of this, and other causes, it is not always possible to achieve exact numerical ratio between the carrier current transmitted from one point and that received at another. Thus, it is preferable to avoid an arrangement in which fault conditions are indicated by a difference between the magnitude of the currents concerned.

A transmission line will be equipped with a circuit breaker at each end and with relays designed to trip the breakers automatically in the event of abnormal currents being carried by the line. The relays may operate on overcurrent, ground current, or may be power-directional. Such relays will correctly indicate abnormal conditions, but, in the general case, do not, by themselves, distinguish between a fault on the line—when we want both switches to trip—and a fault elsewhere, when we wish to avoid interrupting the line.

In order to accomplish this, we must know at each end of the line what is happening at the other end, and it is for this purpose that we employ the carrier-current system.

In ring systems, or networks, a fault generally not only causes a difference in the magnitude of currents entering and leaving the faulty line, but also sets up a difference in direction.

One method of carrier-current protection would be to employ power directional relays at each end and to use the carrier to furnish at one end an indication of the position of the relay contact at the other. Such an arrangement would be quite practical, but a system independent of line potential is to be preferred.

Principle of Operation

The effect of a fault on the normal direction is the feature employed to discriminate. In order, however, to avoid potential excitation, the direction of power is not used, but instead, the instantaneous direction of current. This is done in the following way:

The carrier is not used to trip the circuit breakers when the line itself suffers a fault. If this were done, we could not be sure of proper operation if the line should be connected to a source at one end only; or if the line should break in such a way as to bring about this condition. Moreover, the carrier channel may be interrupted by the fault.

Thus, at each end, overcurrent relays are installed and connected to the oil-switch trip circuit. If the instantaneous currents at each end of the line have the same direction, indicating that the line itself is sound, a carrier signal is received preventing the overcurrent relays from tripping the circuit breakers. This looks after the stub feed, or broken line condition.

If a three-electrode tube oscillator be operated from an a-c. plate voltage, it will oscillate intermittently during those half cycles only when the plate is positive.

In a similar way a bias detector may be supplied with an a-c. plate voltage. It will be inoperative during the half cycles when the plate is negative, but during the positive half cycles, if the grid potential permits, plate current may flow. The grid will be excited

from a source of 180 deg. out of phase with the plate voltage so that normally there will be no plate current, the grid being negative when the plate is positive. If there be impressed on the grid an additional voltage of carrier frequency, a rectified current may be caused to flow in the plate circuit; but this can occur only during a positive half cycle. Thus, we may have a transmitter sending during alternate half cycles and a receiver capable of receiving only during the intervening half cycles. A relay may be placed in the plate circuit of the receiver tube; this will operate when carrier is received.

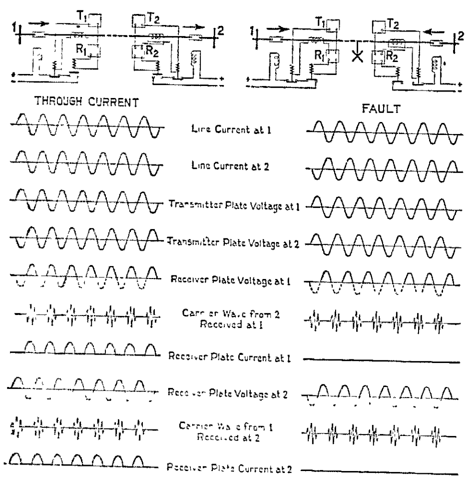

FIG. 1—PRINCIPLE OF OPERATION

Fig. 1 shows, in an elementary manner, how these features may be arranged to furnish the desired result. The diagram represents a transmission line having a circuit breaker and over-current relay at each end. The two ends of the line are designated as "1" and "2" respectively. Carrier-current transmitters T_1 and T_2, at each end, together with receivers R_1 and R_2, are excited from current transformer secondaries. When carrier is received, the receiver relays open the trip circuits and prevent the opening of breakers. The equipment at each end is the same except that, as shown, one of the current transformer secondaries is reversed.

The left hand series of diagrams refers to the case of a sound line which may be supposed to be carrying excess current to a point beyond the bus. It will be seen from the diagram that the primary currents are identical, whereas the plate voltages of the transmitters, which are derived from the current transformer secondaries, are of opposite polarity. The receiver-plate voltages at each end are reversed in respect of the adjacent transmitters. Thus the receiver voltages are also 180 deg. displaced from each other. Each receiver, therefore, is inoperative during the half cycle occupied by the transmission from the transmitter at the same end, and cannot receive from the latter.

Referring now to the transmitter-plate voltages at opposite ends, as shown in the left hand diagram, it can be seen that the positive half cycles occur alternately. Thus the two transmitters, oscillating intermittently, send out pulses of carrier in alternate sequence. The positive half cycles of the receiver-plate voltage are shown in full lines and the negative half cycles, when the receivers are inoperative, are shown in broken lines.

Therefore R_1 is inoperative while T_1 is sending, but can receive from T_2. Likewise R_2 can receive from T_1 but not from T_2. In the case illustrated by the left hand series of diagrams, both receivers are operated and the receiver relays open the trip circuit and thus prevent the over-current relays from tripping the circuit breakers.

The right hand series of curves shows the conditions when there is a short circuit on the line. In this case both the transmitters are sending simultaneously during which period neither of the receivers is able to receive. When both the receivers are operative neither of the transmitters is sending. Thus the receiver relays are not opened and the line is tripped by the over-current relays at each end. The operation of the system, therefore, is such that if a current enters at one end, that end will be opened automatically unless the current is "registered out" at the other end, which is an indication that the line is sound. If a fault be fed from one end only, the transmitter at the other end will not be excited by the current transformer and will not transmit. The fault will therefore be cleared, at the end from which it is supplied, by the over-current relay.

A unique feature of this arrangement is the fact that it is possible to send and receive in both directions at the same time and at the same carrier current frequency. Thus, only a single frequency is required instead of two.

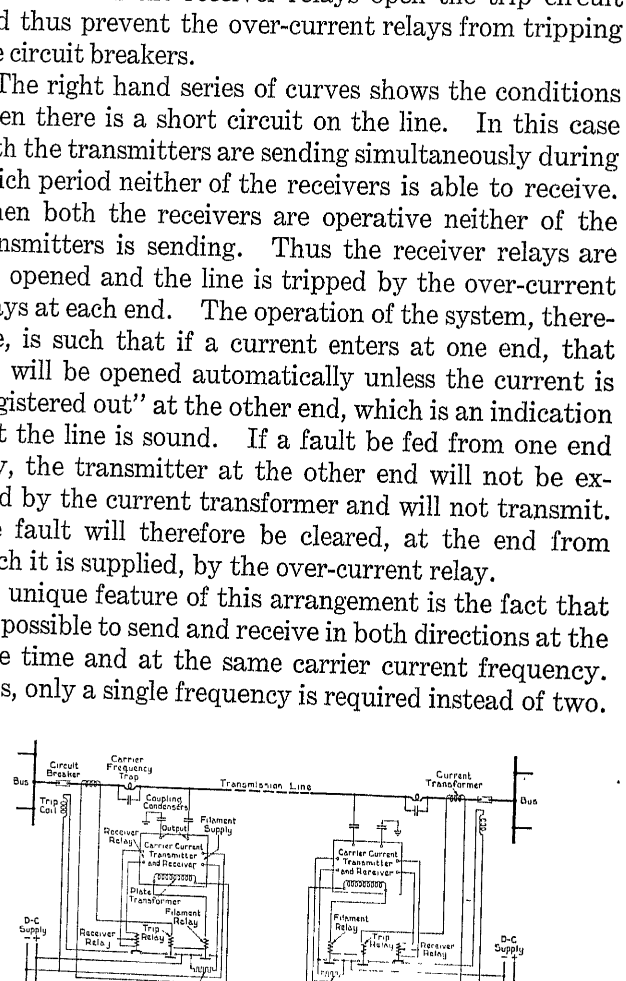

FIG. 2—DIAGRAM OF CONNECTIONS—SINGLE PHASE

This is a distinct advantage if a number of lines is to be protected by this method, and one which will become more evident as the use of carrier current for purposes of communication and control becomes more prevalent.

SINGLE-PHASE CIRCUIT

The actual arrangements employed will now be more readily understood. Fig. 2 shows a complete diagram of the system. With a view to simplicity, only a single-phase line is given in the first instance, and the carrier current apparatus is not shown in detail. It

will be seen that the current transformer is connected in series with the primary winding of the plate transformer and two over-current relays, one of which completes the trip circuit and the other energizes the tube filaments. The former is furnished with a slight, definite, time delay; the latter is instantaneous. A preheating resistance may be connected across the contacts of the filament relay if desired. If the filament be run continuously at reduced voltage, it will have little effect on the life of the tube, but the time taken to raise the filament to full operating temperature will be substantially reduced. If this be done, the time delay of the trip relay need not exceed one-half second. Without preheat, a full second might be necessary.

The trip relay will be set to pick up at a current slightly higher than the filament relay, in order to insure both filament relays closing before either trip relay picks up. The filament relays will be set to operate at a current somewhat exceeding the normal load on the line and not less than that at which the current transformers furnish sufficient plate voltage to operate the transmitting and receiving tubes.

Thus, when an overload occurs on the transmission line, the filament relay first picks up, closing its contacts which connect the filament supply to the vacuum tubes. Within the brief period, necessary for the filaments to reach operating temperature, the carrier-current equipment is fully in operation.

The receiving tube controls a polarized relay, the contacts of which are normally closed. When the carrier wave is transmitted during those half cycles which indicate that the over-current is not due to a fault on the line protected, the receiver tube energizes this relay. Thus, at both ends of the line, the trip circuit is opened and the subsequent closing of the contacts of the trip relays immediately afterwards does not open the circuit breakers.

If on the other hand the fault should be on the line itself, either the carrier does not reach the receiver, or if it is received, does not affect the receiver because it is transmitted, during the half cycles when the receiver is inoperative. The result is the same in either case; the receiver relay remains closed and when the trip relays close their contacts, the trip circuit is completed and the line disconnected.

It will be noted that the line has positive over-current protection under all conditions except when there is a definite indication that it is sound.

Carrier-Current Trap

An important point in the operation of this system is the affect on the channel of reference of faults. While the principle adopted has followed closely that of wired differential schemes, and the general effect of faults will be viewed from similar aspects, certain differences, due to the use of carrier, are of interest.

The occurrence of a fault may or may not lead to the interruption of the channel of reference; that is, the effective transmission and reception of the carrier wave. Assuming a simple coupling, the carrier will be stopped by a broken line, or a short circuit between the phases to which the carrier is coupled, on the section protected. A similar short circuit outside the protected zone may also have the same effect. Thus, it is necessary to provide between the point of coupling and the bus, a trap circuit for carrier. This prevents short circuits, anywhere but on the section protected, from interrupting the carrier. This trap circuit takes the form of a lightning arrester coil tuned, by means of a condenser, to the frequency of the carrier circuit. The condenser

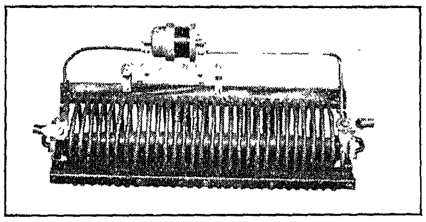

Fig. 3—Carrier-Current Trap

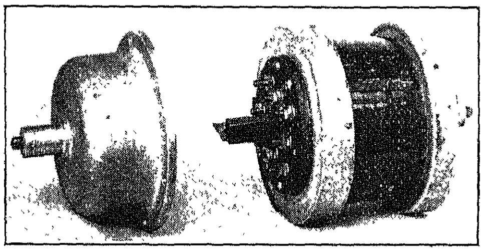

Fig. 4—Carrier-Current Trap Condenser

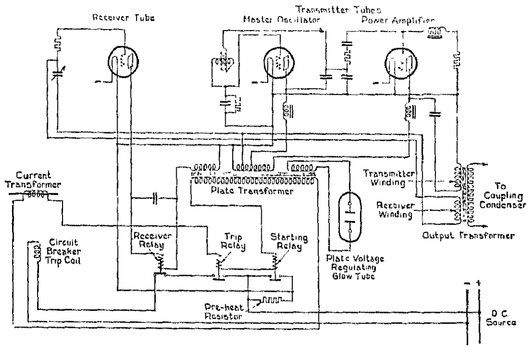

Fig. 5—Carrier-Current Transmitter and Receiver

is mounted directly on the choke coil. It is made in the form of an assembly of several dissimilar capacities brought out to terminals in such a way that a large number of combinations may be obtained. In this way, the trap may be tuned to any one of a number of available frequencies. The condenser is arranged to be readily removed from the coil for this purpose.

The complete trap with the condenser in position is shown in Fig. 3. Fig. 4 shows the condenser dismantled for setting to the desired frequency. The condenser shown has three sections and can be set for 17 frequencies ranging from 40 to 120 kilocycles.

The complete connections for both the relay and carrier current circuits, at one end only, are shown in Fig. 5. Two secondary windings on the plate transformer are required to operate the carrier transmitter and receiver. The transmitter is of conventional form, having one master oscillator tube and one power amplifier, a suitable tap being furnished for the lower voltage required by the oscillator. The receiver is an ordinary bias detector, the negative voltage applied to the grid being derived from a tap to the transmitter winding, since this is of opposite polarity, at an instant, from that of the receiver plate winding.

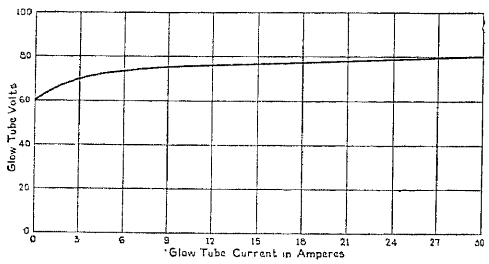

Fig. 6—Regulating Glow Tube Characteristic

Plate Voltage Regulation

One of the principal features of any protective relay system is the extreme range of current value over which it must operate. The apparatus should preferably be capable of functioning with currents not greatly exceeding normal load; yet it must sustain without damage, and work properly at the heaviest short-circuit current which the power system can furnish. In extreme cases, twenty times normal load may be met with.

Since the transmitter and receiver plate supplies are furnished by the current transformer, it is evident that a means must be found for providing a more or less constant voltage over this range of excitation. Vacuum tubes of the type used in carrier-current circuits cannot operate satisfactorily over a voltage range of more than three to one. The problem of extending this range to that required for a protective system entails special treatment. In view of the fact that we must limit the maximum, rather than the effective plate voltage, in order that the tubes may not be damaged during short circuits on the power system, saturated core principles are of no assistance.

This difficulty has been successfully overcome by the use of a special type of regulating glow tube, developed by the company's research laboratory. The characteristics of this tube are shown in Fig. 6. The tube passes no current until the voltage reaches 60 volts, when a visible glow appears. For any value of current up to 30 amperes, the voltage drop across the tube will not exceed about 80 volts. The appearance of this tube may be seen in Fig. 7.

The glow tube is connected to a special secondary winding on the plate transformer, the action of the tube being illustrated in Fig. 8. As the primary current is raised, the voltage across the glow tube winding, and across all other windings on the transformer, will increase up to the point at which the tube commences to discharge. The values of the various plate voltages at this point and at higher values of excitation will be the glow tube voltage multiplied by the respective turn ratios. It will be noted that the tube controls the

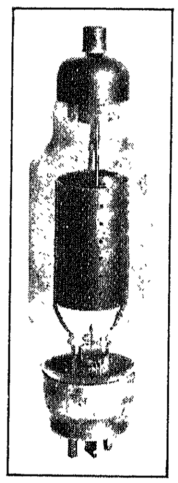

Fig. 7— Late Voltage Regulating Glow Tube

maximum voltage only and does not come into action until the instantaneous value reaches the glow voltage of the tube. The effect, therefore, on the wave form is to furnish a wave which is sinusoidal up to the point where the peak voltage is equal to the glow point of the tube. With higher values of excitation, there is no substantial increase in the maximum value of any of the secondary voltages, but the wave form becomes more

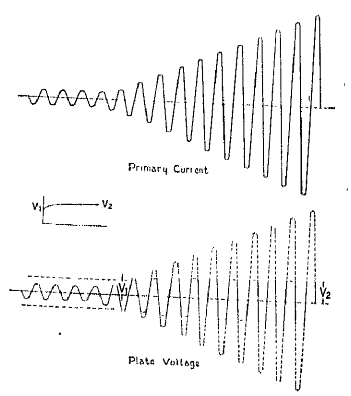

Fig. 8—Action of Glow Tube

and more rectangular. This characteristic is peculiarly favorable to this system of carrier current control in which the operation is independent of the wave form and of the amplitude, being solely determined by whether the wave is positive or negative.

Fig. 9 is an oscillograph record which shows the action of the glow tube. The primary current is varied over a wide range and the resulting effect on the plate voltage,

which would be proportional to the current if no glow tube were present, can be seen very clearly.

Phase Relations

In the explanation of the operating principles of this system, it was assumed that when the line is sound, the two currents will be in phase and that when the line suffers a fault, the instantaneous currents will be of opposite polarity. In the development of this system, it has been necessary to consider to what extent this is actually correct under service conditions.

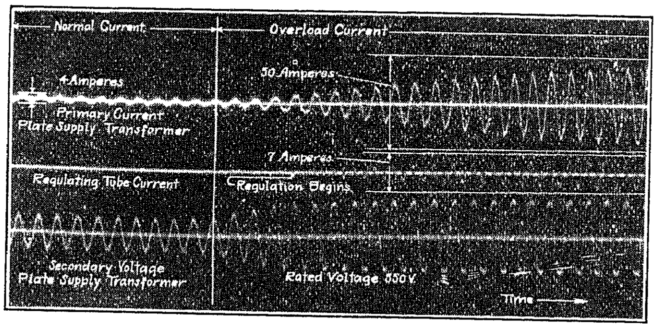

Fig. 9—Primary Current and Plate Voltage

In the case of a "through" short-circuit current, the currents at each end of the line are in actual fact identical, on lines of present length, except for the charging current of the line, which in most cases is small in comparison with the current at which the over-current relays would be expected to operate.

When the line itself suffers a fault, the two currents are not identical. They will usually be of different magnitude but will in general be very nearly 180 deg. apart in phase relations. There may be special cases, however, where the fault is fed from each end through circuits having different impedance power factors which may result in some slight departure from this phase relation, and this possibility has been studied. Fig. 10 is a polar curve which shows the affect on the current in the receiver relay of variation in the phase relation between the primary currents exciting the transmitter and receiver. It is evident that in the case of a "through" short-circuit current, there is no risk of the receiver relay failing to pick up as the currents are identical. In the case of a short-circuit on the line, the relay should not pick up. It can be seen that there must be a difference of at least 45 deg. between the two currents before this can occur.

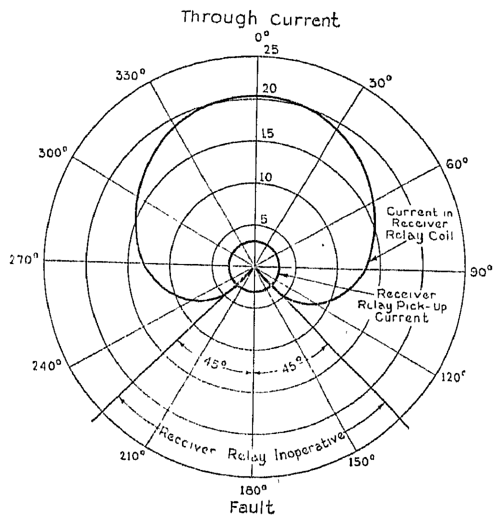

Fig. 10—Effect of Phase Relation Between Receiver and Transmitter

Three-Phase Circuit

In order to apply this arrangement to the protection of a three-phase line, it is not necessary to use three carrier current equipments. All that is required is to furnish an arrangement of primary windings such that any possible fault condition will energize the plate transformer.

It will be necessary to bring the carrier apparatus into action on the occurrence of the following currents. We may refer to the three phase as A, B, and C.

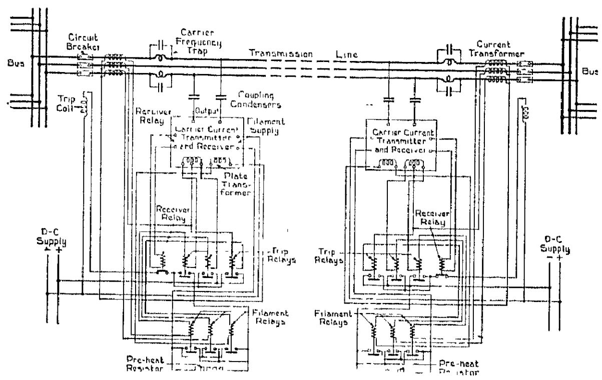

Fig. 11—Three-Phase Diagram of Connections

Three-phase fault on	A B C
Fault between lines	A B
Fault between lines	B C
Fault between lines	A C
Ground fault	A
Ground fault	B
Ground fault	C

The minimum number of exciting windings which will enable each of these conditions to furnish energy is three. By providing, therefore, three windings, of dissimilar numbers of turns, each of the above cases will set up a resultant excitation of the transformer. The magnitude of this resultant will necessarily vary according to which of the above conditions holds. Since, due to the glow tube, the carrier-current system operates over an exceptional current range, this variation will be of no moment, provided that the minimum excitation,—that is, when the least effective combination of turns results,—is sufficient.

It is very often an advantage to be able to furnish more sensitive operation in the case of ground faults than where the trouble arises from a short between lines. Moreover, a ground fault, limited in magnitude, perhaps, by an earthing resistance or maybe by the high

reactance or resistance of the abnormal return path, may not cause complete reversal of the current if an appreciable load is present.

Thus, it may be desirable to so arrange the means whereby the flow of current controls the carrier apparatus

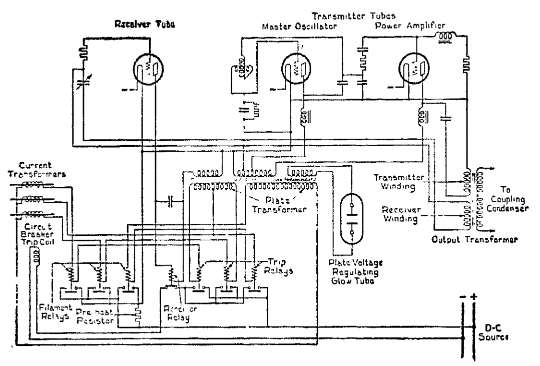

FIG. 12—CARRIER-CURRENT TRANSMITTER AND RECEIVER—THREE PHASE DIAGRAM

that a ground fault has a preponderating influence. We may do this by furnishing two windings of equal turns connected directly in the current transformer secondary circuit and one of an increased number of turns connected in the neutral circuit of the three-current transformers.

Three tripping relays and three filament relays are

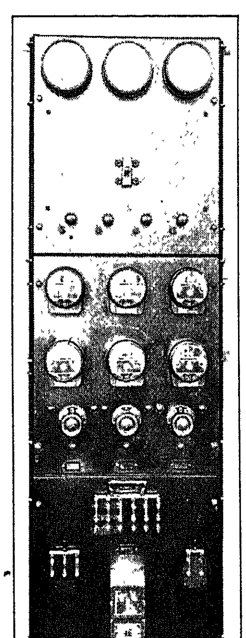

FIG. 13—CARRIER-CURRENT AND RELAY PANEL

employed. In each case, one may conveniently be a ground relay which may be set to operate at a lower value of overload than the others. The general arrangement is shown in Fig. 11.

The complete connections for one end only are given in Fig. 12. It should be noted that the glow tube is energized by all kinds of faults. Therefore, while the primary current at which the glow tube comes into operation will vary according to the nature of the fault, the glow tube will always regulate all the plate and other voltages at the appropriate values corresponding to the turns on the several windings.

CONCLUSION

This system will furnish protection substantially equivalent to that which may be obtained with a pilot wire system, provided that the lowest phase-fault current at which it is desired to operate, is not less than the normal rated current of the line. In the case of ground faults, it is possible to obtain operation at lower values than full-load current.

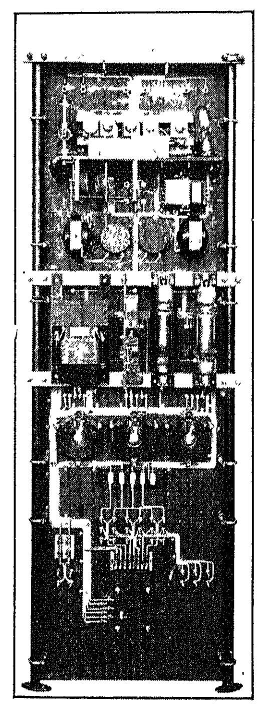

FIG. 14—CARRIER-CURRENT AND RELAY PANEL, REAR VIEW WITH COVER REMOVED

In cases where it is required to take care of phase-fault, short-circuit currents, which are less than full load, it is desirable to install additional filament relays to avoid continuous operation of the tubes during normal load conditions.

The apparatus may be operated from bushing transformers as well as from standard types of current transformers.

Tests have been made on a 66-kv. line about 30 mi. in length. The apparatus was excited from standard bushing transformers. Actual short circuits, both between phases and to ground, were applied to the line itself or at neighboring locations. The system performed satisfactorily with fault currents which ranged from 200 to 1700 amperes.

Fig. 13 shows a front view of the equipment which

was employed for these tests. The upper section of the panel carries all the carrier-current transmitter and receiver apparatus and instruments indicating the filament voltage of the tubes, the transmitter output current and the receiver relay current. The tuning adjustments can be seen in the photograph.

On the middle section are the filament relays, trip relays, and filament rheostats.

The receiver relay is mounted on the lower section which also carries the filament and test switches.

The carrier apparatus may be seen more clearly in the rear view Fig. 14. This section is normally protected by a cover. Back of the center section are mounted the plate transformer and the plate voltage regulating glow tubes of which two are shown in the illustration.

Discussion

E. R. Stauffacher: This novel and effective system of transmission-line protection offers great promise for lines operating at high voltage with a long-distance between stations.

It was my privilege last March to witness some of the tests of this equipment on the Ohio Power Company's system in the section of the system located near Zanesville and between the substations known as Newmark and Crooksville. This carrier-current pilot system of protection was applied to a 66-kv. line between the above stations and the stations were separated a distance of 35 mi. The tests were made on a rainy Sunday, and fourteen tests in all were made by means of putting short circuits within the section protected, and exterior to the section protected. The short circuits were phase-to-phase and phase-to-ground. There was, with possibly one exception, successful operation in all cases. When the short circuits were applied exterior to the section protected, the carrier-current system of protection kept this section in service; when the short circuit was within the section protected it eliminated this section and the short circuit promptly from the system.

One of the tests was particularly outstanding,—Test No. 6. This was a phase-to-phase short circuit between phases 1 and 2, was exterior to the section protected, and was rather severe, the current from one side of the system being 285 amperes, at 66 kv., and from another side 1785 amperes at 66 kv. The total amounts to a short circuit of about 230,000 kv-a.

While that is not so great as may be encountered on this system, still it is a sizable short circuit and for that particular system was enough to result in a very heavy jolt. It was quite interesting to notice the swaying or oscillation of the system for several seconds after the short circuit occurred. I believe that about 10 swayings were observed, swinging back and forth on the ammeter, where thousands of kilowatts were being exchanged across the section protected by this carrier-current protective system—and this section remained intact and stayed in service.

That would have been a very severe test for any directional-relay form of protection, and I doubt if the lines would have stayed in, for the current was sufficiently great to indicate that the short circuit was in that particular section, and the direction of current flow was from one side to the other.

The carrier current was apparently fast enough to keep up with the swayings back and forth, and the section did not trip out.

In conclusion, as I stated before, it appears to me that this system offers great promise. From the observation of the tests it looks as if there was something to be desired in regard to speed. The author informs me that the speed of operation can be increased appreciably by the preheating of the filament and continuous excitation of the plate.

In this particular test 50 per cent preheating of the filament was used, but the time can be cut down, by means of 100 per cent heating of the filament. Here is a case where it is necessary to balance the life of the tubes against the necessity for extra speed in eliminating trouble from the system. We are finding out that the elimination of a fault from the system without making the system unstable, is largely dependent upon speed and my only suggestion to the manufacturers is that they do all they can to speed up operation of this very unique system of differential protection.

Roy Wilkins: (by letter) In protection against line faults there are two major conditions:

1st: Where the short-circuit current, either between the phases or from phase to ground, is several times the normal load current, such as is found in distribution systems in metropolitan areas.

2nd: Where the short-circuit currents are comparable to, or less than, the normal current in the line. Such conditions apply to high-voltage transmission lines, particularly with regard to current from phase to ground, the case most common in practise.

The paper by Mr. Fitzgerald presents a method beautifully simple for applying differential protection to transmission lines. Differential protection has been developed to its highest perfection in England, and a general study of the English methods, difficulties, and results is valuable to anyone interested in relays.

I should like to point out from a practical standpoint some of the difficulties that will be encountered before the carrier-current pilot system can be universally applied to large high-voltage networks. Judging from considerable carrier-current experience with all available present-day makes on extreme high-voltage lines it can be stated that at present existing relay systems are far more reliable than carrier-current installations.

In view of its extra cost, the carrier-current installation to be desirable must give superior performance. Some means must be secured to eliminate the phase-relation troubles mentioned in the paper, because the charging current on a 200-mi. 220-kv. line is often half as great as full-load current, and at low or medium loads may be more than the in-phase current at either end of the line, depending on operating conditions.

It is a perfectly practical condition to have more than 45 deg. between such currents for normal conditions. Lower-voltage networks have relatively little of such troubles.

Another difficulty is that the current in phase-to-ground short circuits greatly varies in power factor, depending upon the location and character of the trouble.

Relays at present in use for ground protection are so connected as to trip in a given direction selectively on as low as 1/4 sec. and on the Pacific Gas & Electric system of some 5000 mi. of line, 60-kv. and above, last year, for over 1500 operations, there was no indication of a faulty operation of a ground relay.

Phase relays depending upon combinations of voltage and current do not present nearly so clean-cut a record.

Finally, the operating time must come down from the present standards—a very great way down,—as a perusal of several of the high-tension papers presented will show.

Differential protection is one of the most desirable forms known, and outside the various split conductors and enclosed pilot wires used on low tension, the carrier system is the initial attempt to adapt it to high tension. It is to be hoped that it can be developed to overcome most, if not all, of its present limitations.

Philip Sporn: (by letter) As pointed out by Mr. Fitzgerald, the differential method of protection of generator and transformer windings has become almost universal and is the only standard and proper method of protecting these important pieces of equipment. The use of the differential circuit in protecting buses has also come very prominently to the foreground within the last four or five years. Abroad, the differential scheme has

been employed to protect transmission lines but it has never found very much favor here and in the main I believe this instinctive engineering act, if you wish to call it that, has been fully justified. If a pilot line is made more reliable than the transmission line, and it must be that to stand up under conditions that would cause the breakdown of the transmission line, then the cost involved becomes so great that economically it becomes prohibitive. If it is not to be built with the same degree of reliability then it is of no use to go to the scheme. The use of carrier eliminates the main reason why the pilot scheme has not found favor here up till now.

To those of us who have had actual experience in trying to obtain selective action on a loop involving four or five, and sometimes six, stations, by the use of reverse-power and induction-type relays only, and who have actually been trying to obtain another 10 cycles differential between two stations, and have known the disappointment that goes with chasing through a set of relay time settings only to find at the very end that there is one condition under which the apparently perfect set of settings would not work, the idea of getting a method of cutting down by one or two, the number of stations that would have to be made so to differentiate will certainly be welcome.

It is hoped that actual operating experience will bear out all the fond hopes that we have for this scheme. On this, as well as on the question of tests referred to by Mr. Fitzgerald, we may have something to place before the Institute within the next year or so.

One other aspect of the differential scheme of protection that ought to be pointed out is the lightning aspect.

Operating experience obtained within the last four or five years on systems where, under conditions of short circuit or flashover, currents in the neighborhood of 3000 to 5000 amperes can be pumped into the point of flashover on a transmission wire, has definitely shown that if the trouble is cleared within a certain minimum time, little burning, if any, will result. I think it can be definitely stated that on systems such as mentioned, if this time is kept below 1 to 1½ sec. no trouble need be anticipated. Further, if the time is made as high as 3½ sec., trouble is to be expected almost always. Now here is an arrangement that in a loop system allows the clearing of a case of trouble within a period say of $^1/_2$ to $^2/_3$ sec. The contribution of such a device to continuity of service, if it develops satisfactorily, is bound to be enormous.

L. F. Fuller: A protective gap is placed around the carrier-current trap so that surges on the transmission line will not pass through the trap but will jump the small gap and pass on. This gap is not shown in Figs. 2 and 11 of the paper.

A. S. Fitzgerald: Mr. Stauffacher has made reference to the speed of operation of this form of protective apparatus. In the first trial installation of this system no especial effort was directed toward attaining any great speed of tripping. We concerned ourselves mainly with an investigation of the operating characteristics of carrier current in this new field of application.

As Mr. Stauffacher indicates, the speed of tripping of this apparatus is not limited to the half-second mentioned in the paper, where reference was made to a circuit in which the over-current relays, which initiate the operation of the carrier-current equipment, were connected so as to control the filament voltage.

Substantial reduction in time can be obtained if, instead, we connect these relays so that they complete the plate-voltage circuit instead of the filament supply. This is now being done in the case of the equipment which the paper describes. The filaments are run continuously, but since the plate voltage is not normally applied to the tube, no emission can take place except when the protective equipment is actually brought into operation. The life of the tubes, of course, depends largely upon the length of time during which there is emission from the filaments.

Mr. Wilkins restricts his remarks to the conditions which are encountered when this system is applied to very high-voltage lines. It is assumed that he has principally in mind systems operating at 220 kv.

Mr. Wilkins entertains some doubt as to the reliability of carrier-current equipment. The number of carrier-current communication installations now in service in the United States on systems up to 132 kv. must exceed 200, and this figure surely suggests that a high order of reliability has been attained. The amount of carrier-current equipment at present installed on 220-kv. lines does not seem sufficient for final conclusions to be drawn as to the results which can be obtained at this voltage. Mr. Wilkins will also appreciate that the function which the carrier current is called upon to perform, is, in the present application, very much simpler than that necessary in the case of carrier-current telephony. There is no question of calling, nor are there any problems of modulation. Furthermore, the transmission of carrier is restricted to the simplest case of a single length of line instead of having to carry right across a complicated network.

The author finds himself in agreement with Mr. Wilkins when he points out that the application of carrier-current protection to 220-kv. circuits will involve the consideration of conditions not met with at lower pressures, and especially in respect to his remarks on the advantages of ground relays in comparison with phase relays. It is not unlikely that the ultimate solution will be found in a carrier-current system envisaging ground faults principally, if not exclusively.

The question of current-phase relation is, perhaps, rather too involved to discuss through the present medium but it may be pointed out that the curve given in Fig. 10 is the result of specific design based upon an estimate of the probable general condition. It is possible to furnish different characteristics if circumstances should require them.

The author shares with Mr. Sporn the hope that this system may ultimately prove to be a real help in the operation of large power systems.

Coupling Capacitors for Carrier Current Applications

BY T. A. E. BELT[1]

Member, A. I. E. E.

Synopsis.—Coupling to high-voltage transmission lines for purposes of carrier-current communication was first universally made by means of coupling wires. This type of coupling usually required high-power transmitting equipment, but when coupling capacitors were substituted it was possible to reduce the carrier input to the line without affecting the received signal strength. The paper gives an approximate method for determining the effectiveness of coupling wires and coupling capacitors. No attempt is made at refinements in calculations as it is only desired to show the effect of stray capacity. Curves show the change in practise from coupling wires to coupling capacitors. It is estimated that by the early part of 1928 the total number of the two types of coupling will be equal. The electrical characteristics for different types of insulation used in coupling capacitors, based on test results is given. Some important points of design for the new cable capacitor are included.

* * * * *

Approximate Method for Determining Effectiveness of Coupling

A simple mathematical treatment only is necessary to show the effect of stray capacity. From experimental data it has been determined that the impedance of a single long transmission line to carrier frequencies is of the magnitude of the surge impedance of the line, and that this high-frequency impedance acts as a straight ohmic resistance load. It has also been shown that ground losses are relatively small for interphase coupling. In the following calculations, therefore, the carrier-frequency impedance of the transmission line will be treated as a resistance and the ground resistance will be neglected.

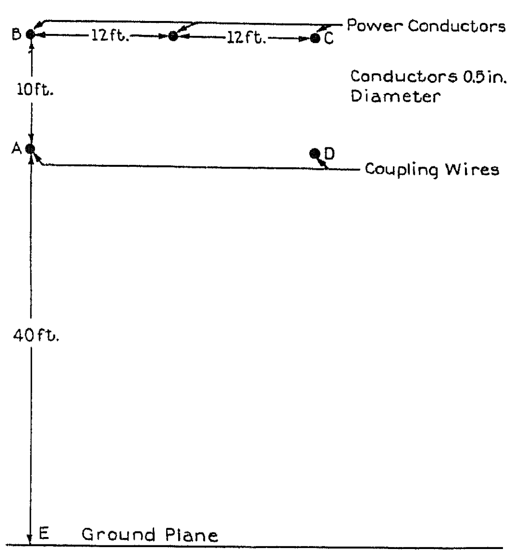

FIG. 1—DIAGRAMATIC ILLUSTRATION OF COUPLING-WIRE INSTALLATION

Fig. 1 is a diagramatic representation of a coupling wire installation. It is assumed that the power conductors are horizontally spaced on 12 ft. centers and the two coupling wires are 10 ft. below the two outside power conductors. The ground plane is assumed to be 40 ft. below the coupling wires. For such a coupling-wire installation, the useful capacity between a 1500-ft. coupling wire and the power conductor is approximately the capacity between A B minus the capacity of A C, which is:

$$C_2 = 0.00205 - 0.00178 = 0.00027 \ \mu \text{ f.}$$

The stray capacities A D and A E between the coupling wires and to ground are of the order of 0.0018 μ f. The equivalent circuit of this coupling-wire installation is represented in Fig. 2.

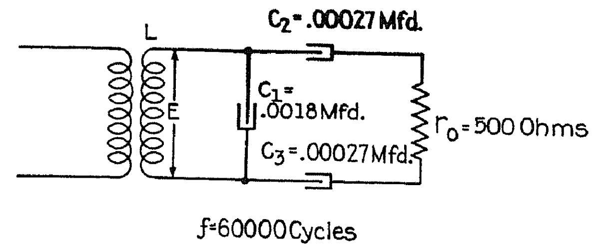

FIG. 2—EQUIVALENT CIRCUIT FOR COUPLING-WIRE INSTALLATION

Let

f = Carrier frequency
 = 60,000 cycles.

E = Applied carrier-frequency potential
 = 100 volts.

C_1 = Stray capacity between coupling wires and ground
 = 0.0018 μ f.
 = 1470 ohms at 60,000 cycles.

C_2 = Effective capacity of one coupling wire to the power conductor.
 = 0.00027 μ f.
 = 9800 ohms at 60,000 cycles.

C_3 = C_2
 = 0.00027 μ f.
 = 9800 ohms at 60,000 cycles.

r_0 = Equivalent high-frequency resistance of the transmission line.
 = 500 ohms.

Z = Impedance using coupling wires.

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Presented at the Pacific Coast Convention of the A. I. E. E., Del Monte, Calif., Sept. 13-16, 1927.

See pp 1051 & 1056 of Sept. Journal of AIEE 1927

Z^1 = Impedance using coupling capacitors.

Then for coupling wires (Fig. 2):

$$\dot{Z} = \frac{\dot{Z}_1 \dot{Z}_2}{\dot{Z}_1 + \dot{Z}_2}$$

Where

$$\dot{Z}_1 = o - j\,1470$$

$$\dot{Z}_2 = 500 - j\,(2 \times 9800) = 500 - j\,19600$$

Then

$$\dot{Z} = 67.4 - j\,1360$$

And

$$Z = \sqrt{67.4^2 + 1360^2}$$

$$= 1360 \text{ ohms.}$$

Therefore

$$I = \frac{E}{Z}$$

$$= \frac{100}{1360} = 0.0737 \text{ amperes fed into network}$$

where coupling wires are used.

With properly designed and installed coupling capacitors, the stray capacity effects are very small and vary considerably with each particular installation. By properly arranged circuits, the capacitance between lead-in wires is relatively small. The stray field between units is also small with proper mechanical spacing. Therefore, we will neglect these stray capacities for purposes of calculating the current required using coupling capacitors.

Fig. 3 represents the equivalent circuit for a coupling-

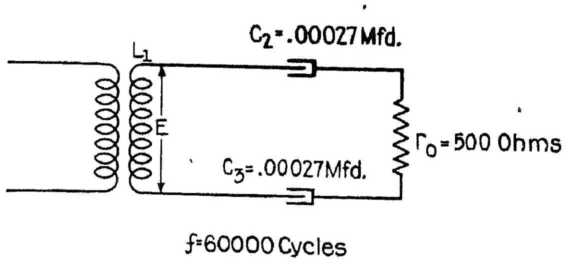

FIG. 3—EQUIVALENT CIRCUIT FOR COUPING-CAPACITOR INSTALLATION

capacitor installation. In order that the calculations may be compared directly with those obtained using coupling wires, the same effective coupling to the power conductor is assumed as before.

Thus for coupling capacitors (Fig. 3):

$$\dot{Z}^1 = 500 - j\,19600$$

$$Z^1 = \sqrt{500^2 + 19600^2}$$

$$= 19600 \text{ ohms.}$$

Hence

$$I^1 = \frac{E}{Z^1}$$

$$= \frac{100}{19600} = 0.0051 \text{ amperes fed into network}$$

where capacitors are used.

We will define the effectiveness of coupling as a per cent ratio:

$$Y = \frac{\text{Useful Current}}{\text{Total Current}} \times 100$$

Then

$$Y = \frac{0.0051}{0.0737} \times 100$$

$$= 6.92 \text{ per cent for coupling wires.}$$

$$Y^1 = \frac{0.0051}{0.0051} \times 100$$

$$= 100 \text{ per cent for coupling capacitors.}$$

As previously stated, there is a small stray-capacity

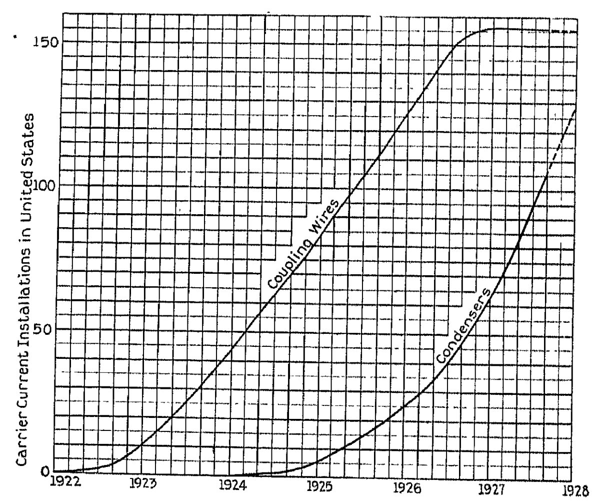

FIG. 4—CURVES SHOWING NUMBER OF CARRIER-CURRENT INSTALLATIONS, USING COUPLING WIRES AND COUPLING CAPACITORS IN THE UNITED STATES

effect when coupling capacitors are used and, therefore, the effective coupling is not actually 100 per cent, but is believed to lie somewhere between 80 and 100 per cent.

CHANGE IN COUPLING PRACTISE

From the relative effectiveness of coupling wires and coupling capacitors, it is not surprising that the change in practise from coupling wires to capacitors has been rapid. Up to the beginning of the year of 1924 there were no coupling capacitor installations in the United States. Fig. 4 shows the number of carrier-current installations using coupling wires and capacitors. Out of a total of 43 installations at the beginning of the year of 1924, all used coupling wires. At the end of 1924, there were 11 installations using capacitors and 97 using coupling wires. At the close of 1927, it is estimated there will be 130 installations using coupling capacitors and 145 installations using coupling

wires; and that in the early part of 1928 there will be as many carrier-current installations using coupling capacitors as those using coupling wires.

Types of Coupling Capacitors

Four distinct types of coupling capacitors are manufactured in the United States:

1. Mica
2. Porcelain
3. Oil Filled Cable
4. Oil Filled Tank

Both the mica and the porcelain type use low-voltage unit construction, that is, the individual units are rated at a definite voltage and capacity. For higher voltage installations series-parallel combinations are used for obtaining the proper voltage and capacitance rating. Some of the characteristics of capacitors, using these different types of dielectrics, are tabulated as follows:

TABULATION OF TEST DATA TAKEN ON 0.001 μf. COUPLING CONDENSERS USING VARIOUS TYPES OF DIELECTRICS

Condenser	Type insulation	Voltage rating	Power-factor per cent at 1000 cycles	Flashover 60 cycles wet r. m. s. volts	Flashover 60 cycles dry r. m. s. volts	Impulse Strength Crest kv.	Impulse ratio
1	Mica	110,000	0.10		585,000	800	0.97
2	Porcelain	132,000	1.670		284,000	300/400	0.75/0.99
3	Oil-filled cable	110,000	0.500	293,000	319,000	800	1.78
4	Tank type (oil and barriers)	110,000	0.500	260,000	355,000	1000/1100	1.99/2.19

On account of lower first cost for medium voltages, the mica and porcelain capacitors have been generally installed on circuits up to and including 66 kv. The oil-filled cable capacitor has a field of application for potentials above 66 kv. The oil-filled tank capacitors are available for 110-kv., 132-kv., and 220-kv. circuits. The 100-kv. and 220-kv. sizes have been in service for a period of approaching two years on several systems throughout the country. Both the Pacific Gas and Electric and Southern California Edison systems are equipped with 220-kv. capacitors.

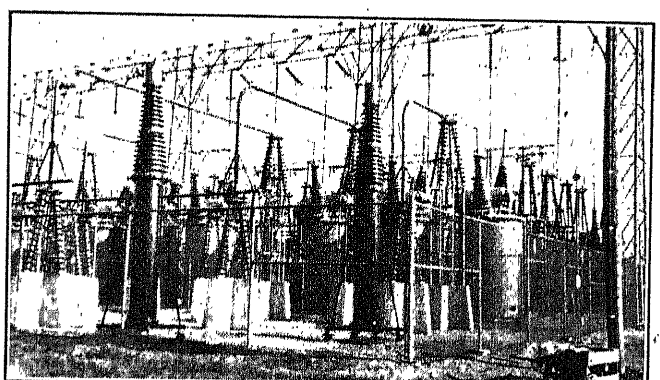

FIG. 5—TANK-CAPACITOR INSTALLATION ON SOUTHERN CALIFORNIA EDISON SYSTEM

Cable Capacitors

The cable and tank[2] capacitors, Fig. 5, are new developments. The cable capacitor, Fig. 6, consists of a short length of paper-insulated oil-filled cable bent into a loop, the free ends of which are stripped of their lead sheaths and brought up through wiping sleeves and electrostatic shields into a porcelain shell, where they terminate in a common terminal. The lead sheath of the cable is attached to the carrier-current output transformer. The whole structure is filled with vacuum-treated oil and hermetically sealed from the atmosphere, so that changing weather conditions do not affect in any way the dielectric strength of the insulation. An expanding metallic reservoir is attached to the capacitor which takes care of the expansion and contraction of the oil caused by temperature changes.

Fig. 6 is a cross-section drawing showing the general details of construction of the cable capacitor for 110,000-volt service.

These capacitors may be mounted on the transmission tower by providing a suitable structural-steel bracket, placed on a base mounting as shown in Fig. 6A, or set up on a framework depending upon the particular requirements of the customer. In the majority of cases the operator will wish to mount the unit outdoor on the steel transmission tower, since the weight of the capacitor—1000-lb.—permits this, and it may be thus placed in a very convenient position at a minimum cost. Connection to the line is then simple and direct; the unit is far enough up so that no surrounding fence is

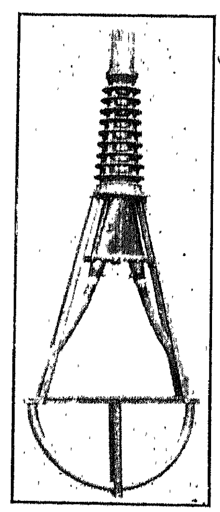

FIG. 6—CABLE COUPING CAPACITOR FOR 110-KV. TRANSMISSION SYSTEM

2. For purposes of brevity it has been necessary to omit the description of the tank capacitor but it is planned to present a paper on this type of capacitor at a later date.

required to protect against marauders, and periodic examination is not handicapped.

The voltage of cable-type capacitors is limited only by the voltage rating of available cable. At the present writing, the highest voltage commercial cable is 132 kv., but 154-kv. cable is now being built for capacitors of this rating, and specifications on 220-kv. cable for a proposed 220-kv. cable-type capacitor have been prepared. For the time being, it is not contemplated that the cable-type capacitor will be developed for voltages below 66 kv. because at the lower voltages the cost is higher than for some other types of capacitors.

The porcelains used on these units are similar to those used for standard oil-filled bushings for power apparatus; so that uniformity of practise in this respect is preserved.

At first glance it might appear that cable capacitors

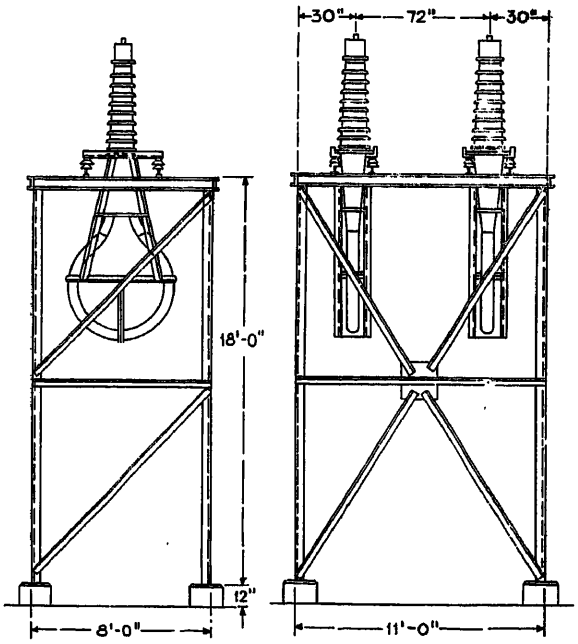

FIG. 6A—FRAMEWORK MOUNTING FOR CABLE CAPACITORS

have considerable inductance due to the loop of cable, but a little thought shows that there is no external magnetic field if connection to the lead sheath is made at the top, for then at every cross-section of the cable the current in sheath and conductor is of the same magnitude, and the magnetic flux is therefore confined to the space between conductor and sheath. On the assumption of a linear distribution of current from the terminal to the low point of the cable loop where the current is zero, (for reasons of symmetry), the total stored magnetic energy corresponds to an equivalent inductance equal to only 1/12th that between the conductor and sheath of the active length of cable employed. This is about 5×10^{-9} henry per ft.

The specially treated paper used in the construction of this cable gives it a capacitance of about 73.2×10^{-6} μf. per ft. Therefore less than 14 ft. of cable has

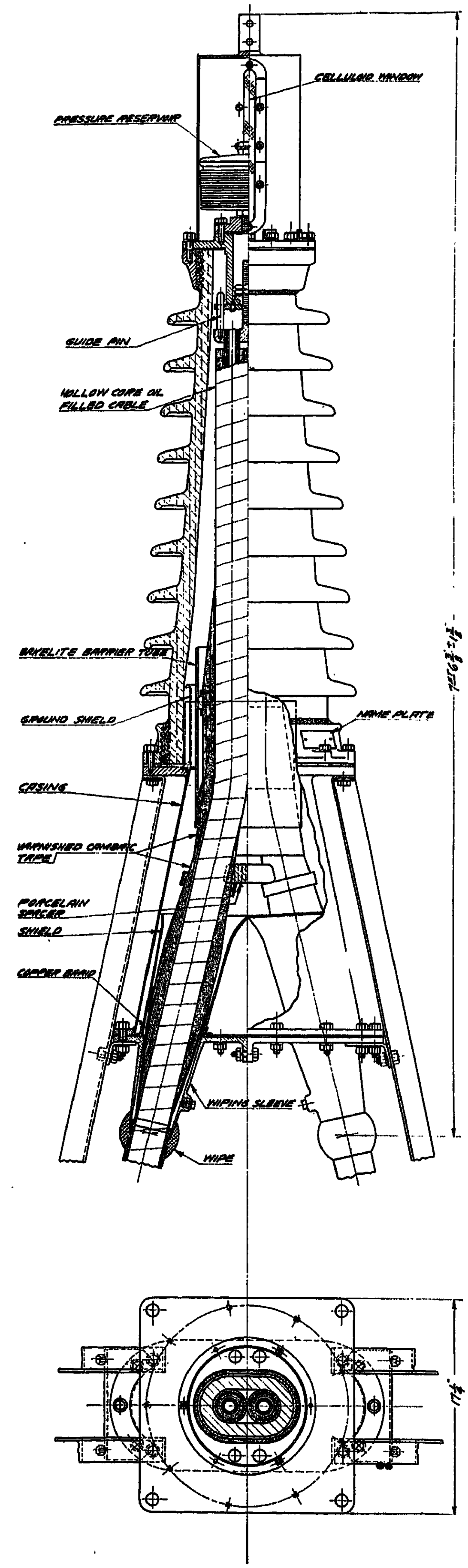

FIG. 7—CROSS-SECTION OF CABLE CAPACITOR

the required capacitance of 0.001 μ f. for coupling purposes. From 75 per cent to 85 per cent of the total capacitance is in the external loop of cable for the 0.001 μ f. units.

In the manufacture of cable capacitors it is important that the bending of the cable be done without wrinkling the paper dielectric. For this reason bending forms are used for shaping the cable loop. The transition from the several lead sheaths of the cable is effected by applying (on a taper) varnished cambric tape overlaid with copper braid until a diameter is reached

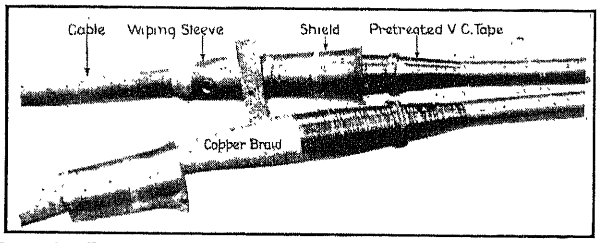

FIG. 8—INTERNAL CONSTRUCTION OF CABLE CAPACITOR

at which a layer of oil may be introduced without exceeding the allowable radial gradient for oil, see Fig. 8. At this diameter a smoothly flared conical shield continues the metal surface until it intersects the wall of the casing. The function of this shield is to increase the thickness of the oil layer at such a gradual rate that excessive longitudinal stresses are avoided. When the flare of the shields has opened out to a sufficient diameter, the varnished cambric is again tapered down to the surface of the cable paper. A small porcelain spacer is inserted to preserve the proper spacing and then a double wrapping of varnished cambric tape applied to serve both as a mechanical binder and to relieve the radial stress on the oil, which increases as the ground shield inside the bushing shell is approached.

The sheet-iron casing is oval shaped at the bottom where it bolts to the wiping sleeves, and then gradually changes to a circle at the top where it meets the bushing shell. The shape and dimensions of this casing have considerable influence on the design. The slope of its walls must not differ enough from the slope of the insulation to cause excessive longitudinal gradients, and must have sufficient clearance to prevent excessive circumferential stresses.

It is important that there always be a positive oil pressure inside the capacitor, so that no air or moisture can enter. For this purpose a pressure reservoir, actuated by an internal mechanism, keeps the oil under a pressure *above* that of the atmosphere. The reservoir is filled at the factory in such a manner as to compensate for the yearly temperature variation at its destination.

On the end castings of the pressure reservoirs there are four small radially projecting guides, which center the reservoir inside its sheet-iron cover. This cover has two celluloid windows through which the position of the reservoir may be observed. A terminal is welded to the top of the reservoir cover, for connection to the transmission line.

VACUUM TREATMENT AND OIL FILLING

In a piece of apparatus of this kind intended for satisfactory operation over an indefinite period of time without attention, except for an occasional inspection, it is of primary importance that its interior insulation be absolutely free from moisture and air. For this reason, hermetically sealed cable capacitors are subjected to a very elaborate and efficient system of factory inspection and vacuum treatment. The bushing shell, casing, and pressure reservoir are individually tested with oil under pressure. During assembly every precaution is taken to keep the internal parts clean and free from moisture or foreign material.

When the capacitor has been assembled, a connection

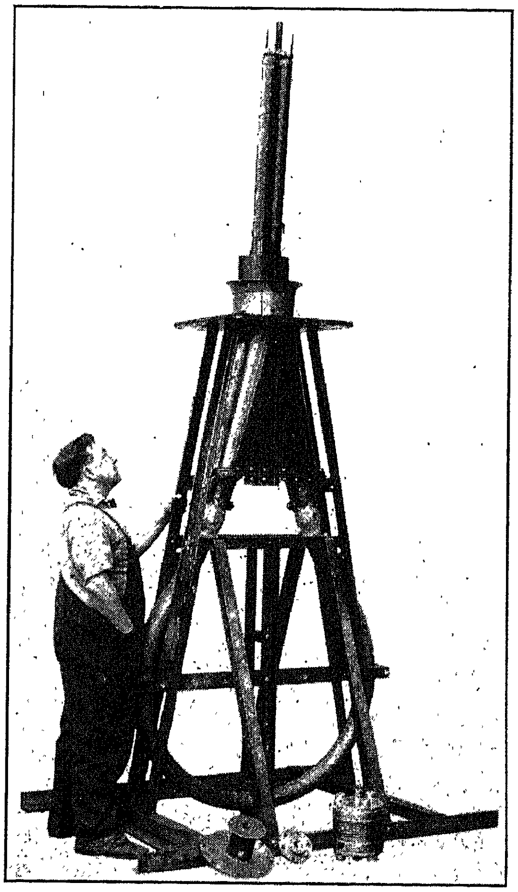

FIG. 8A—PARTIALLY ASSEMBLED CABLE CAPACITOR

to a vacuum pump is made at the top of the bushing, with the pressure reservoir removed. A vacuum of 200 to 500 microns[3] absolute pressure is maintained during the treatment, at the end of which the capacitor is ready for filling with No. 10-C transil oil at 120 deg. cent. which has been kept at that temperature and under vacuum for 20 hours previous to the filling of the capacitor. This oil must test 30 kv. or better between one inch diameter disks spaced 0.1 in. apart.

During the entire vacuum treatment the temperature

3. There are 25,000 microns per inch of mercury.

of the cable is maintained at 100 deg. cent. on the outer lead sheath and at about 140 deg. cent. on the conductor by circulating currents in the cable as the secondary of a transformer.

The filled capacitors are allowed to cool for several hours under a pressure head of 5 lb. per sq. in. After cooling, they are disconnected from the oil and vacuum system and hermetically sealed with their pressure reservoirs. Before sealing, the reservoirs are expanded by oil pressure to the necessary height.

Discussion

E. R. Stauffacher: Fig. 5 shows the installation of the tank-type of coupling capacitors at the Laguna-Bell Substation of the Southern California Edison Company. There is a similar installation at Big Creek No. 3 which totals four units of capacitors for the system. In both of the stations the units are connected to one of the two 220-kv. busses. This equipment has been in service for about a year and has been thoroughly satisfactory in its performance. There was some apprehension at first as to whether or not it was advisable to connect a new and untried piece of equipment to the 220-kv. bus but our experience shows that it is as reliable as any other apparatus designed for the same operating voltage. You can see that it gives a much more finished and workmanlike job than is possible with overhead wire coupling. It is of interest to note the statement regarding the effectiveness of coupling where the coupling wires are credited with a 7 per cent effectiveness of coupling while the effectiveness of the coupling capacitors is rated somewhere between 80 and 100 per cent.

The cable coupling capacitor has not been used on our 220-kv. line and we have no experience to relate concerning it. However, for voltages lying between 66 kv. and 154 kv., it should prove to be a means of making an effective and compact coupling.

Wm. Dubilier: (by letter) I should like to point out certain facts concerning condensers for high-voltage operations:

There is no question as to the superiority of mica as a dielectric in a condenser over any other dielectric at present available. It must be remembered that mica is the only dielectric known which does not deteriorate with time, under electrostatic pressures.

Mica condensers are so constructed that the potentials are subdivided in such a way that individual units carry 1000 volts or less; therefore, the high-voltage problems, such as ionization in the condenser unit, corona effects and other difficulties that may be developed due to impurities of artificial dielectric material, as used in cables and porcelain, are not present with mica.

For the purpose of carrier-wave coupling, the mica condenser has been standardized in units of 22,000 volts. For higher voltages a number of those units is connected in series, eliminating the use of extremely high-voltage insulators necessary with all other types.

Moreover, this unit construction permits keeping only one or two units as spares, requiring considerably less investment, as compared to the types where the condenser unit is designed for line voltage.

Conditions in Europe, especially in territories surrounding Switzerland, are much more severe than are generally experienced in this country, and the electric railroads and power supply companies (such, for instance, as the Chemin de fer du Midi) have been experimenting for many years with every known insulating material, and have finally adopted mica condensers as the most suitable in practically all of their installations operating at 60,000 volts. These capacitors have now been operating with great satisfaction for several years.

A carrier-wave coupling condenser developed in this country is shown in the accompanying Fig. 1. The four separate units are clearly seen mounted on top of each other. Such an installation would be suitable for 88,000 volts; for higher voltages units might be added, one for each 22,000 volts.

Fig. 2, herewith, shows an actual installation at the Sunnyside Substation, Ohio Power Company, Canton, Ohio, one of the properties of the American Gas & Electric Company, installed on their 132,000-volt circuit between Canton, Ohio, and Philo,

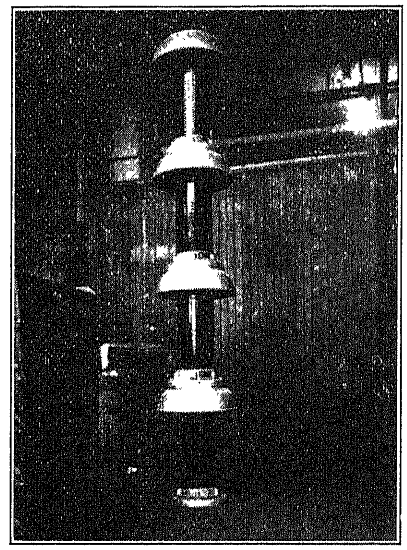

FIG. 1—MICA-TYPE COUPLING CONDENSER

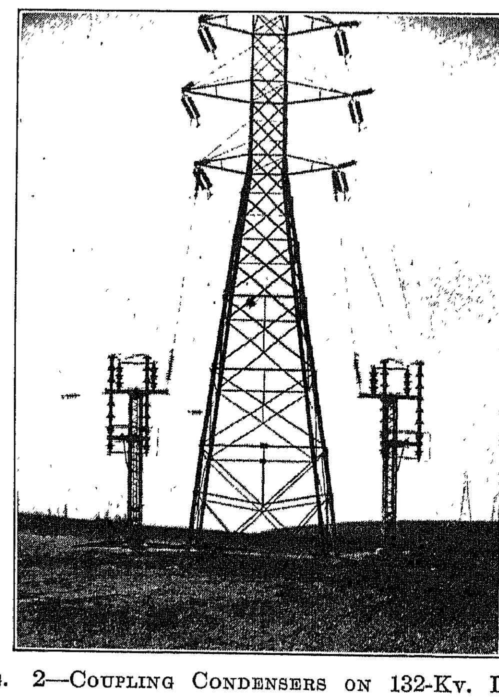

FIG. 2—COUPLING CONDENSERS ON 132-KV. LINE

Sunnyside Substation, Ohio Power Co., Canton, Ohio, one of the properties of the American Gas and Electric Co; installed on their 132,000-volt circuit between Canton, Ohio and Philo, Ohio, March 1925. This installation consists of two columns, six 22,000-volt units in series per phase.

Ohio, March, 1925. This installation consists of two columns, six 22,000-volt units in series per phase.

A number of installations of this nature is at present scattered over the country, and so far the results have fully justified the theoretical considerations which have led to the choice of mica

condensers in preference to other types. Some of the installations have been in continuous use for about three years, and as the carrier-wave connecting system is the link which must be as nearly trouble-proof as possible, it is interesting to note that the majority of the installations have had no trouble whatever, while in other cases the trouble has been due to lightning strokes.

Philip Sporn: (by letter) Mr. Belt has touched upon the question of the increased use of coupling capacitors as against coupling wires and has stressed, as a reason for that, the fact that capacitors have greater effectiveness. I should like to point out however, that while effectiveness has undoubtedly a considerable amount to do with their increasing use, there is another factor which he has failed to point out. This factor has to do with lightning and while lightning is perhaps a subject that does not give much serious trouble in California, in the East and in the Mid-west it is a subject that gives us many a sleepless night.

The work of Peek and others has shown that the ground wire is decidedly useful and very often an almost necessary part of a transmission line where lightning is much of a factor. The klydonograph work carried on by the various companies in the last two years has strengthened that viewpoint. However, whereas a ground wire is important on the line itself, it becomes doubly so at the two terminals of the line where apparatus has to be taken care of. Now what has been the practise with regard to coupling wires? In places where the line has been designed for one or two ground wires, the invariable practise has been to take the last four or five spans of the ground wire, insulate it, and use it as coupling conductor. From the standpoint of the coupling wire, this seemed the logical thing to do, but from the standpoint of the line as a whole, it was decidedly the wrong thing. The result, of course, was to give a line with a rising surge impedance at the two ends and the consequent increment in the steepness of any wave front as it approached the station. This is the reverse of the ideal aimed for, namely the decreasing impedance at the two ends. Viewed in this light, the decision between the coupling wires and coupling condensers is not very difficult. We have something like 22 carrier installations on our 132-kv. system and this involves coupling to approximately 34 different lines practically all of which are made through coupling capacitors. In the vast majority of cases the decision to go to coupling capacitors was influenced to a considerable degree by the considerations outlined above.

From the data on impulse strength of the various types outlined by Mr. Belt, it would appear that the tank type would be the most ideal capacitor. Unfortunately, however, it has the drawback that it is also the most expensive one. Looking for the next best, we find that for a given rating, the mica and oil-filled cable types have about the same impulse strength but the impulse ratios are decidedly different. It would appear therefore that the mica, if it could have 60-cycle flashover value cut down without affecting its impulse flashover, might very well compete with the cable type. In this respect, however, the general characteristics of the mica are not sufficiently well known and it would seem decidedly worth while to have more work done on the subject, particularly as in the present stage mica, from a standpoint of cost, would be decidedly the choice over cable. As regards the porcelain-type condenser (a type not discussed by Mr. Belt), this condenser utilizes materials that have been longest known and tried in the electrical circuit but in the present stage of development it certainly does not look as if it is ready to go on a system where high standards of safety are demanded. More work ought to be done on it.

T. A. E. Belt: Very complete tests at 60 cycles and impulse were made in order to check experimentally the electrical strength of both the cable-type and tank-type capacitors. Therefore, Mr. Stauffacher took little chance in connecting the tank-type capacitors directly to the bus at Laguna Bell and Big Creek No. 3.

Mica is a good dielectric for certain applications, but it has an objectionable characteristic which Mr. Dubilier did not bring out in his discussion; namely, the property of breaking down on steep wave fronts, such as lightning, at a lower value of potential than its maximum 60-cycle breakdown. This characteristic makes it necessary to over-insulate a coupling condenser, using mica for 60 cycles in order to have it stand up in service on a transmission line which is subjected to lightning impulse voltages. There is no measurable deterioration of an oil dielectric such as used in the cable-type and tank-type capacitors.

In general, American practise has not followed European practise, owing to the fact that operating requirements in this country are different from those in Europe and greater reliability is required.

I wish to acknowledge the help given by L. V. Bewley of the High-Voltage Bushing Department of the General Electric Company in the preparation of this paper. I also wish to state that the development of the cable-type coupling capacitor was carried out in cooperation with that department.

The Relation Between Frequency and Spark-Over Voltage in a Sphere-Gap Voltmeter

BY L. E. REUKEMA[1]

Associate, A. I. E. E.

Synopsis.—*The standard instrument for measuring crest values of high alternating voltages at 60 cycles is the sphere-gap voltmeter, which measures a voltage by the distance which it will flash between spheres. In much of the high-voltage research, however, very high frequencies are used. For measuring the voltages used in these high-frequency tests, the sphere-gap voltmeter is used, the assumption being made that its calibration at high frequency is but little, if any, different from that at 60 cycles.*

In the endeavor to make the sphere-gap a standard for measuring peak values of voltage at high frequencies, as it is at present a standard at commercial frequencies, experimental data were obtained from which calibration curves for the sphere-gap voltmeter were plotted for frequencies ranging from 28,000 to 425,000 cycles per sec. for standard conditions of temperature and pressure. These curves cover a voltage range from about 10,000 to 50,000 volts, the source of the high-frequency voltage being a Poulsen arc with variable inductance and capacity in its a-c. circuit. The results show no appreciable change in voltage required to flash across a given gap as the frequency increases until a frequency of about 20,000 cycles is reached, then a gradual decrease in required voltage as the frequency increases from 20,000 to 60,000 cycles, after which a single curve holds for all frequencies at least up to 425,000 cycles per sec., the highest frequency tested. The theory shows that this curve should hold up to a frequency of about 6,000,000 cycles for a one-cm. gap, after which a further decrease should be found. At and above 60,000 cycles per sec., the voltage required to flash across a one-in. gap is 13 per cent lower than the voltage required at 60 cycles, provided only the ions occurring naturally in the atmosphere are available to start the ionization which produces the flashover.

In the course of the investigation it was noted that flooding the spheres with ultraviolet light decreased the voltage required to flash across a given gap at high frequency by about 3.5 per cent, whereas no such effect is found at commercial frequencies. Therefore a complete set of calibration curves for the frequency range covered was also obtained for the spheres flooded with ultraviolet light.

The results are explained by showing that at high frequency a space charge of positive ions will accumulate between the spheres, this space charge distorting the potential gradient sufficiently to allow a spark to pass, even though the average gradient between spheres is considerably lower than is necessary at 60 cycles. The space charge depends on the rate at which ions are added to the field by ionization and the rate at which they are lost by diffusion and mutual repulsion, the terminal condition reached when the rate of gain equals the rate of loss determining the voltage at which flash-over will take place at any given frequency.

One of the prime requisites in all high-voltage research is to be able to measure accurately the voltages employed, and, since it is the peak value of the voltage wave which ruptures insulation, it is especially important to be able to determine this peak value. For such measurements at commercial frequencies, that is, 25 to 60 cycles, the sphere-gap voltmeter, which measures a voltage by the distance which it will flash between spheres, is now the standard instrument. For much of the research in high-voltage phenomena, however, very high-frequency power is used. In much of the insulation testing, for instance, the sources of power are impulse oscillators generating voltages up to 1,500,000 volts or more at frequencies ranging from 30,000 to 500,000 cycles. The sphere-gap voltmeter is the accepted means of measuring such voltages, the assumption being made that the calibration of the instrument is little, if any, different at high frequency from that at 60 cycles. To test the correctness of this assumption was the first object of this research.

In the course of taking the experimental data to determine the relation of frequency to spark-over voltage between spheres, an interesting and important fact was noted, namely, that exposing the spheres to the action of ultraviolet light has a very pronounced effect on the voltage necessary to flash across a given gap. At 60 cycles, the action of ultraviolet light on the spheres is merely to increase the accuracy of the sphere-gap as a voltmeter, but the average voltage required to spark across a gap is neither increased nor decreased to a noticeable extent. At high frequencies, however, a pronounced lowering of the voltage required for a given gap manifests itself whenever a source of ultraviolet light plays upon the spheres. The investigation of this phenomenon, discovered many years ago by Hertz, but apparently overlooked by engineers, constituted the second object of our research.

In any investigation of physical phenomena, the value of the experimental data is considerably enhanced if a rational explanation of the results accompanies them. Such an explanation, on the basis of the fundamental physical principles known concerning electrical discharges through gases, together with an attempt to correlate the newly discovered phenomena with already existing knowledge on the subject, is the third object of the research.

Previous Investigations

The first object of this investigation is not a new problem, as several of the recognized leaders in the development of our knowledge of electrical phenomena have contributed toward its solution. A brief summary of the conclusions reached by former investigators will serve as a fitting introduction to the present investigation.

1. Asst. Prof. of Electrical Engineering, University of California, Berkeley, California.

Presented at the Pacific Coast Convention of the A. I. E. E., Del Monte, Calif., Sept. 13-16, 1927.

See Jl AIEE Mr 1314 1927 Jl 1322

In 1911, J. B. Whitehead and W. S. Gorton started an extensive investigation of the electric strength of air, publishing their results serially in the A. I. E. E. JOURNAL. In one of these papers[2] they state: "There seems, however, to be no doubt that there is a decrease in corona voltage, amounting to about 3 or 4 per cent, in increasing the frequency from 60 cycles to 2000 cycles or over."

L. W. Chubb and C. Fortescue in 1913 investigated the effect of frequency on the spark-over voltage between spheres over the range from 25 to 60 cycles, and found frequency to have no effect in this range.

On June 24, 1914, at the A. I. E. E. convention at Detroit, F. W. Peek, jr., who is responsible for most of the research on the sphere-gap voltmeter, discussed the effect of frequency on spark-over voltage between spheres as one of a number of related investigations carried on, at the General Electric high-tension laboratory, under his direction. He compared a 1000-cycle curve with a 60-cycle curve and found no difference with spark-over voltage plotted as a function of the gap. A 40,000-cycle curve, however, lies below the 60-cycle curve for its entire length, the percentage differences increasing as the voltage increases, from about 11 per cent at 11,000 volts to 16 per cent at 25,000 volts, high frequency. This curve contains only ten points, however, two of them over 10 per cent off of the curve. Moreover, if two points lying below the curve are assumed to be the only ones greatly in error and are disregarded, a smooth curve could be drawn through the remaining points which would raise the curve about 5 per cent. Therefore, this curve could hardly be regarded as conclusive. Moreover, Peek himself does not so consider it. He attributes the decrease in required voltage at high frequency to rough spots on the spheres, as no special care was taken to polish them. In his book, "Dielectric Phenomena in High-Voltage Engineering," 1920 Edition, Peek states: "It seems that the air at high frequency of the above order (40,000 cycles) is only apparently of less strength. If the sphere surfaces are highly polished, it seems that the high-frequency spark-over voltage should check closely with the sixty-cycle voltage. This should also apply for corona on polished wires. The following limitation, however, applies to both cases. At continuous high frequency when the rate of energy or power is great, frequency may enter the energy-distance equation thus

$$A \sqrt{\frac{r}{\delta}\,\varphi(f)}$$

and spark-over take place at lower voltages at very high frequency."

At this same convention, Professors Harris J. Ryan and J. Cameron Clark of Stanford University reported the results of an investigation which they had conducted on the relation of frequency to spark-over voltage, presenting curves of voltage as a function of spark-over distance at three frequencies, 123,000 cycles, 255,000 cycles, and 612,500 cycles. Ryan and Clark drew a single curve through the mean of all points, compared this curve with a 25-cycle curve located by Fortescue and Chubb, and found their own curve to lie almost uniformly 4500 volts below the 25-cycle curve, at least within the range from 20,000 to 50,000 volts. Ryan and Clark used seven-in. spheres, however, while Chubb and Fortescue used spheres 25, 37.5, and 50 cm. in diameter. To determine whether this difference in voltage might possibly be due to a difference in the size of the spheres used, the writer compared the curve of Ryan and Clark, changed to standard conditions of temperature and pressure, with a curve for seven-in. spheres calculated from Peek's formula for spark-over voltage for spheres of any size. In this comparison, the high-frequency curve veers away from the 60-cycle curve more gradually, but at about 50,000 volts the high-frequency curve lies 6500 volts or about 13 per cent below the 60-cycle curve.

Alexanderson also investigated the problem to a slight extent in 1914 with his 100,000-cycle sine-wave alternator, and found that a three-in. gap between five-in. spheres breaks down at about 100,000 volts. He does not definitely state that the high frequency used was 100,000 cycles, nor does he say whether or not one of the spheres was grounded. If it was grounded, as is probable, this shows about a 14-per cent lowering of required voltage at high frequency. Alexanderson used highly polished spheres.

Since the amount of data on the relation of frequency to spark-over voltage by all experimenters combined is rather meager and some of it conflicting, the present investigation was conducted in the hope of clearing up the question, and thus making the sphere-gap a standard means of measuring high-frequency voltages, as it is at present a standard for 60 cycles.

Concerning the second object of the research, the investigation of the effect at high frequency of flooding the spheres with ultraviolet light, literature on the general subject has nothing to say. Apparently this phenomenon has, until our discovery, escaped the notice of both physicists and engineers. Also, so far as we have been able to determine, no one of the previous investigators has tried to show, from fundamental principles, why the required voltage at high frequency should be lower than at 60 cycles.

THE PRESENT INVESTIGATION

The generation of voltages ranging up to 50,000 volts at frequencies of 60 to 500 cycles presented no difficulty, as generators and transformers for these frequencies were available. A diagram of the set-up for the tests is shown in Fig. 1. For the higher frequencies, a two-kw. Poulsen arc, generously loaned to us by the Federal Telegraph Co., was the source of power. For the a-c. circuit of the arc, we constructed a large air condenser

2. The Electric Strength of Air.-V The Influence of Frequency, A. I. E. E. TRANSACTIONS, Vol. XXXIII, 1914, p. 969.

and 24 inductance coils, of open design so as to withstand the high voltages induced, and with a minimum ratio of resistance to inductance, so as to obtain a maximum induced voltage. The inductance coils and the condenser are connected in series across the arc, the leading reactance of the condenser neutralizing the lagging reactance of the inductance coils, so that only the high-frequency resistance of the circuit limits the flow of current. The voltage built up across the coils and that across the condenser neutralize each other, so that either one may be over a hundred times as large as the d-c. voltage impressed across the arc. The high voltage between the condenser plates is impressed across the sphere-gap voltmeter. By varying the distance between the condenser plates and the number of inductance coils used, the frequency may be varied over a range from 28,000 cycles to about 450,000 cycles per sec. according to the formula

$$f = \frac{1}{2 \pi \sqrt{L C}}$$

where f is frequency in cycles per sec., L is inductance in henrys, and C is capacity in farads.

To measure the voltage impressed between the spheres, three condensers in series to break up the voltage were used, a gold-leaf electroscope reading the voltage drop across the middle condenser. The electroscope reads effective values of voltage, whereas it is peak value which causes a flashover; therefore the wave forms of the low-frequency voltages, over the entire range of voltages used, were photographed with an oscillograph and the oscillograms analyzed mathematically to determine the ratios of effective to maximum voltages for this range. The voltage waves from the Poulsen arc were investigated with a sensitive wavemeter, and all harmonics found to be negligible, so that they may be assumed to be pure sine waves within a very small fraction of one per cent.

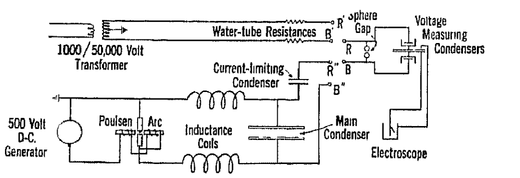

FIG. 1—DIAGRAM OF CONNECTIONS FOR CALIBRATING SPHERE GAP AT HIGH FREQUENCY AND HIGH VOLTAGE

DESCRIPTION OF APPARATUS

The sphere-gap voltmeter was constructed according to A. I. E. E. specifications. The spheres are of brass, 6.25 cm. in diameter and accurately turned. The lower sphere is movable in a vertical direction, and the gap may be readily read to a thousandth of an inch. Neither sphere was grounded.

Since the high-frequency voltage obtainable from a Poulsen arc equals $\frac{E}{R}\sqrt{\frac{L}{C}}$, in which E is the voltage across the a-c. terminals of the arc, R is the resistance of the a-c. circuit, L is the inductance of the coils, and C is the capacity of the condenser, a high ratio of inductance to resistance is necessary in the coils in order to induce the large voltages desired. The resistance of the coils at high frequency is many times that at 60 cycles, due to both skin effect and to eddy-current loss in the copper caused by the magnetic flux of the coil cutting the turns. The coils used were designed to make this high-frequency resistance a minimum, using formulas developed by C. L. Fortescue and published in the Sept., 1923 issue of the *Journal of the British Institution of Electrical Engineers.* Twenty-four coils were constructed, 30 in. in outer diameter and 12 in. in inner diameter, containing eight layers of three turns each, turns being mounted on wooden pegs and spaced one in. apart. The smallest high-frequency resistance for this size of coil is obtained by using No. 9 B & S gage wire.

The principal considerations in the design of the condensers used in series with the inductance coils were to keep the energy losses down to a minimum and to prevent the formation of corona. Energy losses increase the effective resistance of the circuit and therefore decrease the voltage obtainable. Corona, in addition to wasting energy, introduces a source of error into the sphere-gap readings by setting up minor surges in the circuit, which may cause flashovers between the spheres even though the fundamental voltage which is being measured may be much too low. These considerations, together with the high voltages used, called for large condenser plates separated sufficiently by air to prevent flashes between them, and free from sudden bends, sharp corners, and irregularities of any kind. The plates used measured seven by eight ft. and were constructed of galvanized iron nailed to wooden frames, with quarters of copper float balls soldered to the four corners and with metal connectors soldered to the sides to receive the connections from the inductance coils. To prevent stray electrostatic flux from these condenser plates from spreading out into the voltage-measuring apparatus, grounded shields of fine-mesh chicken wire, stretched on pipe frames, were hung on both sides of the condenser.

In parallel with the sphere-gap were three air condensers in series, the middle one of the three having a much larger capacity than that of the two outer ones. These condensers divide the voltage between them in inverse ratio to their capacities, so that the voltage drop across the middle one was about two per cent of the total voltage impressed across the sphere-gap. This voltage drop across the middle condenser was measured by means of a gold-leaf electroscope, connected in parallel with the condenser. The plates of all of the condensers are of galvanized iron on wooden frames supported in vertical planes, and are free from sharp edges and rough spots, with joints covered with tinfoil to prevent the formation of corona, since it is

essential for accurate work that the losses in the condensers be negligible at all frequencies. The plates of the middle condenser are five ft. sq. and one in. and a half thick, are suspended from insulated supports, and are separated about three-eighths of an in. by small porcelain insulators. Each of the outer condensers consists of an outer plate two ft. sq. and one in. and a half thick, which fits inside a boxlike plate, with a bottom three ft. sq. and sides one ft. high, the plates being separated about five in. The smaller plates are connected to the voltage to be measured. Each of the boxlike plates is connected to the adjacent plate of the inner condenser, the boxes facing away from each other. In this way the electrostatic flux from one outer plate is prevented from reaching the other, and also from setting up a stray field in the vicinity of either the sphere-gap or the electroscope. Each condenser is insulated from ground by small porcelain insulators.

The electroscope consists of a nickeled steel case with glass front and back, down the center of which extends a nickeled brass rod carrying the gold leaf. To prevent possible external flux from penetrating the interior of the electroscope, the glass front and back were threaded both horizontally and vertically with fine wires. The rod bearing the gold leaf is insulated from the case by sulphur. A protractor was arranged to turn on an axis in line with the point of connection of the gold leaf, a line peep-sight directly in front of the protractor and a frame carrying a fine hair about four in. behind the protractor turning with the latter as an integral part. This makes it possible to read the deflections of the gold leaf to the tenth of a degree, which compares favorably with the accuracy of the sphere-gap itself.

Whenever a spark takes place between the spheres, a short circuit is produced across the transformer in the case of the low frequency and across the Poulsen arc in the case of the high frequency. To prevent the burning and pitting of the spheres which would otherwise result from such short circuits, water-tube resistances were placed in both high-tension legs of the transformer circuit, and a one-μ f. condenser successfully limited the flow of current from the high-frequency circuit. The voltage drops in the water-tube resistances and in the current-limiting condenser occurred before the voltage was impressed on the sphere-gap and measuring condensers and therefore were in no sense a source of error in the measurements.

The source of ultraviolet light with which the spheres were flooded was an open arc light, ordinarily used for oscillographic work, which was placed about four ft. from the spheres with the light concentrated on them.

Procedure

As the sphere-gap voltmeter is a standard instrument for the measurement of high voltage at 60 cycles, the electroscope was calibrated by reading its deflections for spark-overs between the spheres for voltages ranging from about 7000 to 55,000 volts effective, the voltage being varied by varying the field of the alternator. Since the object of the research is to compare the high-frequency voltage corresponding to a given gap with that required at 60 cycles, this method eliminated the errors which would have crept in if the electroscope had been calibrated with direct current and the capacities of the condensers measured. The readings of the sphere-gap were reduced to standard conditions, 760-mm. pressure and 25 deg. cent., as adopted by the A. I. E. E., and were also corrected for wave form, since the sphere-gap measures crest values and the electroscope effective values of voltage. Although the generator supplying the 60-cycle power produced a practically pure sine wave, the voltage drops within the transformers due to the harmonics of the exciting currents and the distortion due to the internal capacity of the 50,000-volt transformer produced a slight change in wave form, which necessitated the mathematical analysis of the voltage wave on the high-tension side of the transformer, for the range of voltages used in the test. Oscillograms of these waves at six representative values of voltage were analyzed, and the ratio of maximum to effective value of the actual waves compared to this ratio for a pure sine wave. The corrective value averaged about 0.8 per cent and in no case was larger than 1.8 per cent.

The electroscope and measuring condensers having been calibrated for a given setting of the condensers, high-frequency runs were taken, reading electroscope deflections as a function of distances between spheres for the maximum range of voltages obtainable at any one frequency. Temperatures and barometric pressures were recorded, so that the gap readings might later be reduced to those for standard conditions. The voltages were varied by changing the d-c. voltage impressed on the Poulsen arc, the length of the arc-gap, and the strength of the magnetic deflecting field so as to give steady operation. Frequencies were varied by changing the number of inductance coils used and the distance between the main condenser plates. Frequencies were calculated from the wavelength readings of a wavemeter. Runs averaging approximately 100 readings each were taken for frequencies ranging from 28,170 to 425,500 cycles, both with the spheres flooded with ultraviolet light and without. Runs at 133 cycles, 250 cycles, and 500 cycles were also compared with those for 60 cycles. In order to be sure that the particular setting of the measuring condensers was not a source of error, runs were taken for several different settings, each setting requiring a separate electroscope calibration. The surfaces of the spheres were kept highly polished at all times, by polishing them with a power buffer at least once and usually several times during each run, and by hand with a soft towel after each spark-over.

To obtain a reading, the distance between spheres was made slightly greater than could be flashed across by the voltage impressed, then the spheres were slowly moved together by turning the control wheel until

the spark occurred, at the same time keeping the peep-sight of the protractor arrangement trained on the deflected gold leaf, so that the voltage at the instant of flashover could be read accurately. The spheres were always moved together at least a full turn of the control wheel before a flash took place, so as to avoid any error

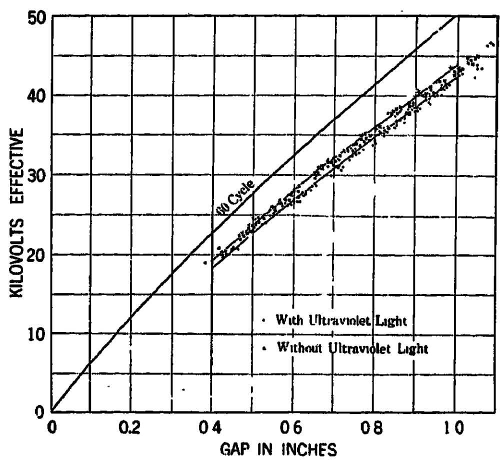

FIG. 2—CALIBRATION OF 6.25-CM. SPHERES AT 95,540 CYCLES

due to lost motion in the control wheel. In case the voltage at the instant of flashover was unsteady, the reading was thrown out. Care was taken to bring the voltage from the Poulsen arc up to the maximum possible with the d-c. voltage impressed before taking a reading, so as to eliminate errors due to surges.

DATA AND CURVES

The publishing of the 50 pages of data secured would serve no useful purpose, since the curves show the results obtained. Moreover, of the many pages of curves

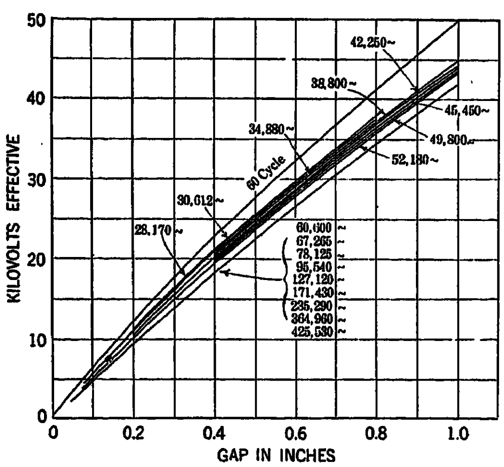

FIG. 3—CALIBRATION OF 6.25-CM. SPHERES AT VARIOUS FREQUENCIES USING ULTRAVIOLET LIGHT

plotted, only three are included in this paper. Fig. 2 is included to show approximately the accuracy with which the points fall on the various curves, and the very evident difference between the voltage necessary to flash across a given gap when the spheres are flooded with ultraviolet light and when they are not. The fact that all points do not fall accurately on the curve when ultraviolet light is flooding the spheres is due to a slight unsteadiness which is inherent in the Poulsen arc, not to any inaccuracy of the sphere-gap itself. Using ultraviolet light, 60-cycle curves always repeat themselves accurately, no point falling more than a quarter per cent off the curve. When ultraviolet light is not used, any point may be as much as two per cent off the curve.

Figs. 3 and 4 show the final results of the test, the one when the spheres are flooded with ultraviolet light, the other when the spheres are not so flooded.

THEORETICAL EXPLANATION OF THE RESULTS

Mechanism of the Spark. Before considering the phenomena of electric discharge through gases, it may be advisable to recall certain fundamental concepts of the constitution of matter. All matter is composed of molecules in continuous motion, the temperature of any substance being merely a function of the energy of

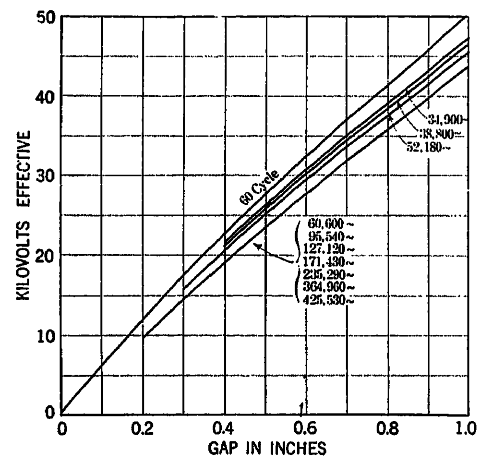

FIG. 4—CALIBRATION OF 6.25-CM. SPHERES WITHOUT ULTRAVIOLET LIGHT

motion of its molecules. In a gas, such as our atmosphere, the molecules are relatively far apart, and the continual collisions of molecules with each other and with the walls of the containing vessel give rise to the pressure of the gas. The average distance traveled by a molecule before colliding with another molecule is known as its mean free path. All molecules, in turn, are composed of atoms, different combinations of the 92 kinds of atoms producing the millions of varieties of molecules. The atoms are composed of a central nucleus with a positive electric charge and of particles of negative electricity, called electrons, which travel around the nucleus in precessing elliptic or circular orbits at enormously high speeds, the electrical attraction of the positive nucleus for the negative electrons balancing the centrifugal force produced by these speeds. An atom thus may be compared to a solar system, its volume being mostly empty space. The number of planetary electrons in a neutral atom is always equal to the number of equivalent positive charges of the nucleus.

It is possible for an atom to lose an electron, however, in which case it is called a positive ion, since the loss of a particle of negative electricity leaves the rest of the atom positively charged. Similarly, a free electron is able to attach itself to most atoms. When this happens, the atom with its extra electron is called a negative ion. An ion, whether positive or negative, behaves like an ordinary molecule, as long as it is not in an electric field. As soon as an electric field is produced, however, the ion adds to its haphazard molecular motion a motion in the direction of the field, toward the positive electrode if a negative ion, toward the negative electrode if a positive ion. If this motion takes place in a vacuum, so that the mean free path of the ion is large, a comparatively small voltage drop, about 16 volts for air, is sufficient to give the ion such a high velocity that it is able to knock an electron out of a molecule with which it collides. This potential is known as the ionizing potential of the molecule, that is, the potential necessary to knock out one of its electrons and thus make an ion of it. As the pressure of the gas increases, however, the mean free path decreases until at atmospheric pressure the air molecule has a mean free path of only about 0.000004 in. In such a short distance it does not have the chance to acquire the ionizing speed except at very high potential gradients.

Whenever a molecule is ionized, the electron which is knocked out of it also feels the force of any electric field in which it finds itself. As an electron weighs only about one sixty-thousandth part as much as an oxygen molecule, however, and since the acceleration which an object undergoes in a given field is inversely proportional to the square root of its mass, its acceleration is evidently about 240 times that of an ionized oxygen molecule. Moreover, due to its increased speed and its much smaller size, its mean free path is four times the square root of two or 5.66 times that of the molecule. The electron, therefore, will attain a velocity many hundreds of times that attained by an ion in the same field. Moreover, because of its smaller weight, as compared with that of a molecule, the electron cannot lose more than a small fraction of its energy in an ordinary collision with a molecule. Thus it gradually accumulates velocity until the average amount it loses per collision equals that gained between collisions, the terminal velocity being a function of $\frac{E}{d}$, where E is potential gradient and d is density of the air. If the amount of energy represented by this terminal velocity is as great or greater than the energy necessary to ionize a molecule, such an ionization may take place, the probability of the ionization increasing rapidly with increase in velocity, up to velocities far beyond any which would be given the electron in air by an electric field.

Now let us consider the mechanism of the electric spark between two electrodes with a potential gradient between them. Even though this potential gradient is far greater than that necessary to ionize the air molecules, no spark will take place unless there are either ions or electrons present to start the ionization. A few ions per cubic centimeter are practically always present in the air, however, and new ones are being formed, mainly by the action of the penetrating radiation recently investigated by Millikan and by radioactivity, at the rate of about 12 per sec. per cu. cm. The electron starts to ionize at a considerably smaller potential gradient than does the ion, and even though it ionizes only once for every thousand collisions, an electron would increase to approximately 485,000,000 in moving one cm. For instance, the mean free path of the electron in air at atmospheric pressure is about 0.00005 cm. If it ionizes once in a thousand collisions, it would ionize about 20 times per cm. The rate of increase in the number of electrons, due to ionization by electrons alone, is given by the equation

$$n = n_0 e^{ax}$$

where n is the number of electrons after the initial electrons have moved a distance x in the direction of the force, n_0 is the number of electrons at $x = 0$, a is the number of ionizations per centimeter, and e is equal to 2.71828, the base of the Napierian logarithm. Since in our assumption a equals twenty, n equals one, and x equals one,

$$n = e^{20} = 485{,}122{,}000$$

However, one coulomb of electricity equals 6,280,000,000,000,000,000 electrons, so that this enormous number of electrons would have to be formed per second to have just one ampere of current pass. Moreover, as fast as these electrons are produced by ionization, they are swept into the positive electrode, leaving only the small number spontaneously formed by radiation or by radioactivity to carry on the work. Evidently, therefore, ionization by electrons alone will not produce a spark.

For each electron set free by collision, however, there is also produced a positive ion, which is attracted in the opposite direction from that taken by the electrons. If the potential gradient is sufficient to allow positive ions to ionize air molecules by collision, or to knock electrons out of the negative sphere, the number of electrons produced, immediately increases enormously. Suppose that only one in a thousand of the positive ions produced was able to ionize and that this ionization took place close to the negative electrode, where the potential gradient would be greatest. Then one electron, with the help of the electrons which it sets free by collision, produces 485,000,000 positive ions while moving one cm. Of these positive ions, 485,000, each ionizing once, then produce 485,000 new electrons, which, starting close to the negative electrode, each produce 485,000,000 positive ions in moving one cm., or a total of 235,000,000,000,000. One one-thousandths of these, or 235,000,000,000, produce

235,000,000,000 more electrons close to the negative electrode, which in turn produce 485,000,000 times 235,000,000,000 electrons, and so on, all of this happening in a very small fraction of a second. The process is thus cumulative, the number of ions and electrons increasing at an enormous rate, and resulting in a flashover between the electrodes. Note that ionization by both electrons and positive ions is essential, and that, since the electron ionizes at a lower potential gradient than does the positive ion, the probability of ionization by the latter is the factor which determines the potential gradient necessary to produce a spark between the electrodes. This potential gradient has been found to be 30,000 volts per cm. under standard conditions of temperature and pressure.

The reason for the increased accuracy of the sphere-gap at low frequencies when ultraviolet light shines on the spheres is now easily understood. The action of the ultraviolet light is to liberate electrons from the spheres, a phenomenon which has been named the photoelectric effect. Thus, when the spheres are flooded with ultraviolet light, there is always a large number of electrons in the space between the spheres to start the ionization, and the instant the potential gradient reaches a value of 30,000 volts per cm., a spark takes place. When, on the other hand, the small number of ions found naturally in the air must be depended upon to start the ionization, there may be no ions available at the instant the potential gradient reaches the required value. This is especially true in the sphere-gap voltmeter, in which the potential gradient gradually increases as the spheres are moved together. The gradient, before it has reached the value required for ionization by collision, simply sweeps into the spheres whatever ions are present, so that when the potential gradient does reach 30,000 volts per cm., the diffusion, into the space between electrodes, of ions from the outer space must be depended upon to start the ionization. This may take an appreciable part of a second or even more, during which time the spheres are being moved closer together, with the result that a higher potential gradient seems to be required to flash across the gap than actually is required. Thus, the determination of a voltage by means of a sphere-gap voltmeter, which is not subject to the action of ultraviolet light, may be one or two per cent in error.

Effect of High Frequency

To understand the effect of high frequency on the voltage required to spark across a given gap, we must consider such phenomena as the mobility of ions, their diffusion, and the variation of potential gradient by space charge. The effect of the attachment of electrons to molecules and the recombination of electrons with positive ions to form neutral molecules is negligible in the high electric fields used. The mobility of an ion is the velocity with which it moves in an electric field. The mobility constant is the velocity in centimeters per second attained by an ion, at 760-mm. pressure and 0 deg. cent., per volt per centimeter of field acting upon it. This constant for positive ions in air is 1.32; for negative ions, 1.8. In high fields, the mobility is nearly independent of temperature, so that the error would be small if one neglected to correct gas ion mobilities for temperatures above 200 deg. K. The mobility of *electrons* does not vary directly with potential gradient, so that for electrons there is really no such thing as a mobility constant. The mobility is a function of $\frac{E}{p}$, however, where E is potential gradient in volts per cm. and p is pressure. According to a curve for electron mobility in nitrogen in a paper by Compton in the *Physical Review* of 1923, an electron in nitrogen at atmospheric pressure would attain a velocity of 13,800,000 cm. per sec. under the action of a potential gradient of 30,000 volts per cm., or it would be swept across a gap of one cm. in $\frac{1}{13{,}800{,}000}$ sec. For air, instead of nitrogen, the figures would not differ greatly. A positive ion, under the same conditions in air, would attain a velocity of 30,000 times 1.32 or 39,600 cm. per sec. If the field were an alternating one, the velocity would vary as the voltage varied. For a pure sine wave of 30,000 volts per cm. effective value, the distance traveled by an electron in one sec. in the direction of the force would be 12,160,000 cm.; by a positive ion, 35,650 cm. Evidently at 60 cycles both ions and electrons would practically all be swept out of the field every half-cycle, so that until the potential gradient has reached 30,000 volts per cm., there could be no appreciable accumulation of space charge to distort the field.

Consider the same phenomena at high frequency, let us say at 50,000 cycles per sec. The electrons are practically all swept into the spheres every half-cycle, just as at 60 cycles. The positive ions have time to move, however, for a gradient of 30,000 volts per cm. only about 0.35 cm. during a half-cycle, so that there is a rapid accumulation of positive ions in the space between the spheres, these ions simply surging back and forth between the spheres as the potential gradient reverses every half-cycle.

Consider the effect of this positive space charge on the distribution of the total voltage between the spheres. If there were no space charge, the electrostatic flux lines would all extend from the positive to the negative sphere, and although the potential gradient would be lower halfway between the spheres than it would be close to the sphere surface due to the spreading out of the flux lines, the distribution of the potential gradient would be symmetrical with respect to the spheres. When a positive space charge is present, however, the flux lines do not all extend from the

positive to the negative sphere. All of them end on the negative sphere, but many of them extend out to the positive ions in the space between the spheres, instead of to the positive sphere. Since the potential gradient is proportional to the density of the electrostatic flux lines, it follows that the potential gradient between spheres is distorted, constantly increasing as the negative sphere is approached, or at least being greater near the negative sphere than it would be if the positive space charge were not present. Therefore, even though the total voltage would otherwise not be able to cause positive ionization, this distortion of the field increases the potential gradient close to the negative sphere sufficiently to allow the positive ions to ionize there, where their ionization is most effective in producing a consequent large number of electrons by electron collision as the electrons produced by the positive ions move to the positive sphere. The voltage required to spark across a given gap, therefore, should be less at high frequency than at 60 cycles, because of the distortion of the potential gradient by the positive space charge.

Let us see how large the effect of this positive space charge may be. Consider two spheres, 6.25 cm. in diameter, one cm. apart, with a potential gradient of 30,000 volts per cm. at the surface of each sphere along the line joining their centers. The electric charge per square millimeter of such surface would be 0.0265×10^{-9} coulombs to give this gradient at the surface, which is equivalent to $0.0265 \times 10^{-9} \times 6.28 \times 10^{18}$ or 166,400,000 excess electrons on one sphere per square millimeter of surface, and an equal deficiency on the other sphere. To appreciably distort the potential gradient along the line connecting the spheres, it is therefore necessary that the space charge, within a column one mm. square joining the spheres, be an appreciable fraction of 166,400,000 ions. If the space charge amounted to the full 166,400,000 ions per sq. mm. column, all of the flux lines leaving the negative sphere would end on ions in the space, and the gradient at the positive sphere would be zero. If the distribution of ions were uniform in such a case, the potential gradient at the negative sphere would be approximately twice the average gradient. Actually the distribution is not uniform, but the ions are concentrated mainly near the spheres, as is evident when one consideres their method of production. The potential gradient would then change rapidly in the vicinity of the spheres, but the maximum gradient would still be approximately twice the average gradient. If the space charge amounted to 20 per cent of this 166,400,000 ions per sq. mm. column, the maximum gradient would be increased about 10 per cent. This increase would hold for a 20 per cent space charge, regardless of the distribution of the space charge, as long as the distribution was symmetrical with respect to the spheres, as it would very nearly be for high-frequency voltage impressed across the gap. To produce at high frequency a 14 per cent increase in the maximum potential gradient as compared with the maximum potential gradient corresponding to a total voltage between spheres at 60 cycles would require about 37,000,000 ions of space charge per sq. mm. column one cm. long connecting the spheres along their line of centers. When one considers that a single electron, ionizing 20 times in traveling one cm., is responsible, with the aid of the electrons it sets free, for the production of 485,000,000 positive ions, it is evident that a space charge of 37,000,000 ions per sq. mm. column per cm. is not only possible, but may be formed in a very small fraction of a second, provided the positive ions are not swept into the negative sphere as soon as formed, as is the case at 60 cycles, but are held in the field, merely oscillating slightly about positions of equilibrium, as is true at high frequency. This explains why a smaller voltage is required to produce a spark across a given gap at high frequency than at 60 cycles.

Let us now consider the effect on the space charge, and therefore on the voltage for a given gap, of gradually increasing the frequency. At 30,000 volts per cm. effective value, we have found that the average velocity of the electron over a half-cycle is 12,160,000 cm. per sec. Therefore an electron could get across a one-cm. gap up to a frequency of about 6,000,000 cycles. The corresponding velocity of the positive ion is 35,650 cm. per sec. Therefore a positive ion could be held oscillating between spheres for a frequency as low as 18,000 cycles, provided it were formed at just the right part of the cycle. At such a frequency, however, only a small percentage of the positive ions formed would be held in the space between spheres, the rest being sucked into the spheres. Therefore only a small space charge would accumulate, and the voltage necessary to produce a spark would be very little less than that required at 60 cycles. As the frequency increases, the distance the positive ions move in a half-cycle decreases, until at 60,000 cycles this distance is only 0.297 cm. for a potential gradient of 30,000 volts per cm., and correspondingly less for any smaller gradient. Note how many ions are now held in the field. If an electron, on the average, ionizes 20 times in traveling one cm. in the direction of the field, $\left(1 - \frac{1}{e}\right)$ or 63.2 per cent of the positive ions, when the first stream of electrons is sucked out of the gas, are within a twentieth of a cm. of the positive sphere; $\left(1 - \frac{1}{e^2}\right)$ or 86.4 per cent are within two-twentieths; 95.02 per cent, within three-twentieths; 98.77 per cent, within four-twentieths, etc. At the end of the first cycle, however, all of these ions have moved away from this sphere a distance of 0.297 cm. for a 30,000-volt gradient, and, except for the effect of diffusion, these ions cannot be captured by the spheres. If we assume that half of the maximum voltage of the cycle is necessary to allow the electrons to

ionize appreciably, so that the first appreciable ionization occurs when one-sixth of the half-cycle is completed, all of the first ions formed which were produced within $\frac{0.297}{6}$ or 0.05 cm. of the positive sphere will be sucked into the sphere during the following half-cycle. This leaves 36.8 per cent of the ions to accumulate for the space charge, since the assumption that the electrons ionize 20 times per cm. means the production of $\left(1 - \frac{1}{e}\right)$ or 64.2 per cent of the ions within 0.05 cm. of the positive sphere. Of the ions formed at the first third of the half-cycle, 13.53 per cent accumulate for the space charge; of those formed 30 deg. later, 4.98 per cent accumulate, etc. Thus approximately 10 per cent of all the ions formed are held for the space charge, neglecting the effect of diffusion.

This effect, however, is not negligible, since the rate at which the ions are lost by diffusion increases with the concentration of the ions. The number lost by diffusion is given by the formula

$$N = D \frac{d\,n}{d\,z} d\,x\,d\,y$$

where N is the number diffusing per second across the area $d\,x\,d\,y$ when the space rate of change in the concentration in the z direction is $\frac{d\,n}{d\,z}$, and D, the diffusion constant, equals 0.028 for positive ions in dry air and 0.032 in moist air. Since $\frac{d\,n}{d\,z}$ for large ion concentration may be many millions, the number of ions lost by diffusion is far from negligible, and, since the number of ions formed per second is practically independent of ion concentration, and the number lost by diffusion increases with increase in concentration, evidently a terminal condition will be reached when the rate of ion loss equals the rate of gain. This terminal condition determines what space charge will be accumulated, and therefore how much the potential gradient will be distorted.

Since the terminal condition depends on the rate of ion gain, it is at once evident that a lower voltage should be required at high frequency when the action of ultraviolet light provides an ample supply of electrons in the gap to start the ionization than is required when the number of electrons is limited to those naturally at hand. The decrease in the required voltage as the frequency increases is also easily understood, since the higher the frequency the larger is the percentage of ions which are retained in the gap, and therefore the larger is the rate of ion gain. But above a frequency of 60,000 cycles, we find that the voltage required to flash across a given gap no longer decreases with an increase in frequency. To understand this, we must consider the distribution of ions in the gap at different frequencies The distribution is always symmetrical with respect to the spheres. At the lowest frequencies at which it is possible for a space charge to accumulate, the distribution throughout the gap is fairly uniform, since the ions can move almost across the gap in a half-cycle. As the frequency increases, the ions tend more and more to concentrate close to the surfaces of the spheres, since this is the position in which most of them are produced and the time allowed for them to move away is inversely proportional to the frequency. This concentration near the sphere surfaces, of course, increases the loss of ions by diffusion, and at some frequency this increased loss of ions must neutralize the increased rate of production. Our data show that this frequency is about 60,000 cycles per sec., both when the spheres are subject to the action of ultraviolet light and when they are not. That the action of ultraviolet light should not change this limiting frequency is predictable from our theory, since the effect of concentration of ions near the sphere surface in increasing diffusion depends merely on the frequency, not on the rate of ion production.

Comparison of Present Results with Those of Previous Investigators

Since other investigators used spheres of various sizes and the voltage necessary to flash across a gap depends on the size of the spheres, actual voltages for a given gap will not check. The percentage variation of the high-frequency curves from the 60 cycle curves should be substantially the same for spheres of all sizes, however, and the results of other men should at least approximately check our own, provided all results compared are fairly correct. The data of Ryan and Clark were taken for 123,000, 255,000, and 612,500 cycles, a single curve being drawn through all of the points. This curve, changed to standard conditions and plotted on the same sheet with a 60-cycle curve, calculated for seven-in. spheres, may be compared with our own results. For a one-in. gap, their high-frequency curve lies 13 per cent below the 60-cycle curve; for the same gap our curve lies 12.8 per cent below, a very close check. A comparison with Peek's 40,000-cycle curve shows his high-frequency curve to lie considerably lower than our own. Peek's own conclusion, however, is that its extreme lowness is due to rough spots on the spheres, as no special care was taken to polish them. The comparison with Alexanderson's results can be qualitative only, since he gives results only for 100,000 volts, a higher voltage than we used. Also he does not definitely state the frequency used, although the text would seem to indicate that it was in the vicinity of 100,000 cycles. Moreover, he does not state whether or not one sphere was grounded. If one sphere was grounded, as it probably was, his high-frequency curve lies about 14 per cent below the 60-cycle curve, which agrees very well with our results. Alexanderon's

spheres were highly polished. No results for tests at frequencies between 60 and 500 cycles have been published. The fact that our curves for 60, 133, 250, and 500 cycles all coincide, however, as theory says they should, leaves little doubt as to the accuracy of these curves. The close agreement of the results of Ryan and Clark and of Alexanderson with our own for the few frequencies tested by these investigators gives us confidence in the reliability of our other curves for which no comparison with previous investigations is possible.

Conclusion

The effect of high frequency is to decrease the voltage necessary to flash across a given gap between spheres. This effect starts at about 20,000 cycles, and increases up to about 60,000 cycles, after which there is no further change.

At and above 60,000 cycles, the voltage required to spark across a one-in. gap is about 13 per cent lower than at 60 cycles, provided only electrons occurring naturally in the gap are available to start the ionization.

At high frequency the voltage corresponding to a given sphere-gap depends on whether or not the spheres are acted upon by ultraviolet light, the effect of this light being to reduce the required voltage by about 3.5 per cent.

A fairly wide variation in the intensity of the ultraviolet light makes no perceptible difference in the voltage necessary to produce the flashover, although it probably does change the time necessary to set up the space charge.

That the space charge, when ultraviolet light is used, reaches a terminal condition in a small fraction of a second is shown by the theory. Our results corroborate this, as far as they go. For instance, while taking the run at 127,120 cycles, using ultraviolet light, a gap of 0.827 in. flashed across when the electroscope deflection was 61.1 deg. The reading was repeated, the gap being left at 0.827 in. and the voltage being brought up gradually until the deflection of the goldleaf was 61.0 deg. This voltage was held for 3½ min. without a flashover taking place. The instant the deflection became 61.1 deg., the flash occurred, just as it had for the preceding reading. Evidently, when ultraviolet light is used, the distortion of the potential gradient occurs almost instantly, a wait of 3½ min. not changing it so much as one part in 600.

That this is not true when ionization is left to the ions found naturally in the air is demonstrated by the relative inaccuracy of the sphere-gap under these conditions.

Our tests disagree with the prediction of Peek that if the spheres are highly polished no difference should be found in the voltage required to spark across a given gap at high frequency and at 60 cycles. Moreover, we do not believe that a *slight* roughness has any appreciable effect. Undoubtedly, rough spheres will allow a spark to pass at a lower voltage than will polished spheres, the rough points forming starting points for corona, and for very rough spheres this effect will probably be greater at high frequency than at 60 cycles. The slight tarnish due to several hundred flashovers is not sufficient to show any such effect, however. At both 60 cycles and at high frequency our tests showed absolutely no difference in the sparkover voltage required, whether the spheres had just been polished on a power buffer or whether as many as 1000 flashovers had preceded the ones measured since the spheres were polished.

The effect of frequency on sparkover voltage between spheres depends on the distortion of the potential gradient by the positive space charge which accumulates in the gap at frequencies above about 20,000 cycles per sec. For each frequency the space charge which accumulates, and therefore the minimum voltage which will allow a spark to pass, depends on the relative ratio of production and of loss of positive ions.

The photoelectric action of ultraviolet light on the spheres makes available a large number of electrons in the gap at all times to start ionization. The difference in the rate of production of positive ions, thus brought about, explains the decreased voltage required when the spheres are flooded with ultraviolet light.

The increased percentage, as the frequency increases, of the positive ions which are held in the gap to form a space charge, explains the gradually decreasing voltage required to spark across a given gap as the frequency increases, up to 60,000 cycles per second.

The increased concentration of the space charge close to the surfaces of the spheres, with its consequent increased loss of ions by diffusion, explains the fact that above 60,000 cycles there is no further decrease in the voltage required to spark across a given gap, at least not until the frequency is above about 6,000,000 cycles for a one-cm. gap, when ionization by electrons alone should be sufficient to produce a spark, the electrons moving a distance less than the gap in a half-cycle, and therefore accumulating in the gap.

In conclusion we wish to express our debt to the many persons from whom we have received aid. Professors L. B. Loeb, C. L. Cory, and G. L. Greves have guided the research and helped with many valuable suggestions. Mr. R. P. Crippen worked jointly with the author in the early part of the investigation, and a large share of whatever of value the work contains should be credited to him.

We are indebted to the Regents of the University of California for financial assistance which made possible the research, and to the Federal Telegraph Co. for its generous loan for several months of a two-kw. Poulsen arc.

Mr. Pemberton and Mr. Cox of the University of California aided in the construction of the apparatus.

I would acknowledge with special gratitude the

splendid cooperation of my wife, who has worked with me far into the night for months in the accumulation of the experimental data, and whose cheery optimism throughout the research has been an inspiration.

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Discussion

H. J. Ryan: The paper of Professor Reukema contains an important addition to the facts and their understanding regarding the frequency-voltage flashover relation of the sphere-gap voltmeter.

It may not be generally known that the voltages employed in some of the long-distance radio communication services are about on a par with those employed in long-distance transmission of power. The losses in the air and other insulating media functioning in the long-distance high-voltage radio transmitters occur at critical values, above which they increase with enormous rapidity.

It is vital, therefore, to have reliable means for measuring the crest values of such radio-frequency voltages. Because such voltages always conform closely to sine voltages, their effective values are deduced from reliable sphere-gap crest voltages with corresponding reliability.

The author has employed excellent strategy; he has most liberally applied well directed energy and enthusiasm to the study upon which the paper is based. I believe that his theory will be helpful in extending the calibrations and uses of the sphere-gap for all voltage frequencies and values.

Those taking up such work should remember the author's discovery of the effect of ultra-violet light upon the manner in which the sphere-gap voltmeter functions, and the promise it gives for the improvement of sphere-gap voltmeter consistency.

May I add just a word in regard to the point-gap discharge at radio-frequency high voltage. In 1915, one of my graduate students and I made a limited study of this subject, and from the results obtained at the time I can confirm the author's impression in regard to the behaviour of point-gaps. We employed a comparatively blunt point discharge to a plate. The plate was grounded; so was one terminal of the 88,000-cycle source. 46,000 volts discharged through 14 in. (See *Proc.* I. R. E., Vol. 3, p. 362.) The radio-frequency kv. per in. diminished as the distance from the blunt point to the plate was increased from 2 to 16 in. At 2 in. the kv. per in. equaled 4, and at 16 in., 1.4 kv. per in.

Regarding harmonics set up by the arc in these studies: The cathode-ray cyclograph was used to observe the presence or absence of harmonics in the undamped high-voltage radio-frequency waves developed by the arc. They were absent.

R. J. C. Wood: It is quite encouraging to find out what Professor Reukema has shown us,—that there is only 13 per cent diminution of voltage required over a given gap when the frequency increases up into the hundreds of thousands.

When we were going through the birth-pains of the 220-kv. lines, we were told in certain quarters that we were going to encounter a great deal of difficulty from high frequencies, which would enable comparatively small voltages to jump enormous distances. Very fortunately we seem to have established the fact that the higher frequencies do not exist in the line, so that removes that trouble, even if it were a fact that high frequency would jump great distances.

I should like to ask Professor Reukema whether he has carried this investigation beyond the point of using spheres—whether he has found any relation with point-gaps; presumably the decrease in the voltage between spark-points is considerably less at high frequencies than it is between spheres.

F. O. McMillan: I should like to ask Dr. Reukema whether he has done any experimental work on the measurement of high-frequency voltages with one sphere of the sphere-gap grounded. The published results as I understand the curves, are all for the ungrounded sphere-gap.

It may be possible that some of the reduction in the high-frequency sphere-gap spark-over voltages found in these experiments may have been due to the capacitance to ground of the apparatus shifting the voltage distribution on the dividing condensers for the electroscope during the high-frequency measurements, the voltage division becoming normal when the 60-cycle voltage was applied on account of the neutral ground on the 60-cycle transformer.

D. I. Cone: In the work of which this paper is a record extraordinary precautions were taken to test the presence of harmonics in the wave. I believe it would be helpful for Dr. Reukema to describe these tests more fully.

Joseph Slepian: Mr. Reukema has made a very valuable contribution to our knowledge of spark-over in air at atmospheric pressures, and in the development of an explanation of his results, has given us an extremely lucid picture of the Townsend theory of spark-over depending on the cumulative interaction of ionization produced by the collisions with molecules of both the positive and negative ions.

Lest there be misunderstanding, however, one point should be particularly stressed, and that is that the observed lowering of the sparking potential is a result of the application of *sustained* high-frequency voltage. If the voltage is applied in the form of rapidly damped pulses or wave trains, the sparking potential is raised and not lowered, as was shown by Leontiewa and Algermissen.

The success which Mr. Reukema has in explaining his results

on the basis of the Townsend theory brings out sharply the dilemma to which Rogowski called attention recently in the *Archiv fur Elektrotechnik.* The Townsend theory has been extremely successful when applied to gases at low pressures, and even at atmospheric pressure will account for the observed relation between sparking potentials and electrode size and spacing. However, since it makes essential the ionization by collision of positive ions, it requires for the development of the spark a time at least longer than the time for a positive ion to traverse the spark-gap. Hence with Mr. Reukema's value of 39,600 cm. per sec. for the velocity of the positive ion under a gradient of 30,000 volts per cm. it would take at least 25 micro-seconds for the spark to develop for a 1-cm. gap. Actually, however, spark-over occurs in a fraction of a micro-second when potentials slightly above the sparking potential are applied. Until this difficulty is cleared up, the use of Townsend's theory at atmospheric pressures will be open to question.

It may be that simple ionization by collision is adequate to represent the very first stages of the development of the spark, but that after a certain critical density of ionization is reached, which takes only a very small fraction of a micro-second for ordinary sparking-potential experiments at atmospheric pressure, Townsend's description of the phenomena in terms of the two ionizing constants α and β becomes inadequate. In that case Mr. Reukema's theory of the lowering of the sparking potential by sustained high frequency need concern itself only with the development of a critical density of ionization, and does not need to be tied up with the Townsend theory of the development of the spark itself.

L. E. Reukema: The first question concerns the effect of high frequency across needle-gaps as compared with the effect across the sphere-gap. It seems to me that the same factors would come in, but to a more pronounced degree when using needle-gaps. In sphere-gaps no corona can form before the break-down occurs. A positive space charge accumulates at high frequency, but no more corona would form than at 60 cycles, which is none at all. With needle-gaps we have corona forming, and the higher the frequency the greater the loss due to the formation of the corona. Whenever corona forms we have both electromagnetic radiation and increased temperature, both of which produce more ionization.

I have no experimental data on needle gaps, but I should say that the effect of high frequency on the needle-gap would be greater than on a sphere-gap.

As to the effect of grounding one sphere, naturally when one sphere is grounded a lower voltage will produce a flashover than if one is not grounded, simply due to the fact that this will distort the electrostatic field so as to produce a higher gradient at one sphere than would exist if one sphere were not grounded. However, it seems to me that grounding one sphere would not appreciably change the results we obtained at high frequency.

I did not make the test because the accuracy of my method depended on having the electroscope at essentially ground potential when I made the measurements. If one sphere were grounded, it would necessarily throw the electroscope off ground potential, which, as Mr. McMillan suggests, would introduce an error due to the capacity between the electroscope and ground.

Although I did not make the test, however, I thought of it quite thoroughly, and judging from the results obtained and the theory involved it seems to me that the results should be very nearly the same whether or not one sphere is grounded. The curves themselves would not hold, but the fact that the curves lie a certain percentage below the 60-cycle curve would hold. The same percentage drop should hold when one sphere is grounded as when it is not.

The possibility of error in the results due to the presence of harmonics in either 60-cycle or high-frequency waves has been suggested. Three years ago I had the privilege of talking this subject over with Dr. H. J. Ryan, and he told me then what he has told now, that the effect of the harmonics is negligible in the high-frequency wave obtained with the Poulsen arc, especially when the amount of inductance used is very large, as it was in my experiments.

However, to be absolutely sure that any harmonics present were negligible, careful tests were made with a wave meter. When testing for the fundamental frequency, the needle of the wave meter would be thrown off scale if the meter were brought closer than about 5 ft. from the inductance coils used. However, with the wave meter set for any harmonic of the fundamental, the meter could be brought right up to the coil, indeed, could be placed inside the coil, without any perceptible movement of the needle. Evidently, therefore, none of the harmonics was large enough to produce a perceptible deviation from a pure sine-wave form for the high-frequency waves.

For the production of the 60-cycle voltage an alternator was used which gave practically a pure sine wave. However, certain small irregularities in the wave form were brought in by the harmonics in the exciting current of the transformers used, these harmonics causing a very slight voltage drop in the transformers and a resultant slight change in wave form.

For that reason, on the high-tension side of the transformers, a series of oscillograms was taken for the range of voltage used in the tests. These oscillograms were then analyzed carefully. The maximum deviation of form factor of the waves tested from that of pure sine waves was 1.8 per cent, the average deviation was 0.8 per cent, certainly much too small to account for more than a negligible part of the 13 per cent decrease in flashover voltage found for high frequencies. Moreover, these deviations were definitely taken into account in plotting the curves, so that wave form could not bring in an error of more than about 0.1 per cent.

Mr. Slepian's statement that the results hold only for *sustained* high-frequency waves is important. For waves generated by Poulsen arcs, vacuum tubes, or high-frequency alternators the curves are accurate. For the damped waves of an impulse oscillator, they do not hold, since the time between successive wave trains is sufficient to change radically the space charge between the spheres, which is the cause of the decrease in flashover voltage at high frequency.

The Space Charge That Surrounds a Conductor in Corona

BY JOSEPH S. CARROLL[1] and JOSEPH T. LUSIGNAN[2]

Associate, A. I. E. E. Associate, A. I. E. E.

Synopsis.—A qualitative analysis of the nature of the space charge created about a conductor in corona, particularly with respect to relative magnitudes and polarities, rather than actual quantitative measurement, is described here. This work was the principal work on corona during the past year in the Ryan High-Voltage Laboratory.

In tests with the arrangements of a wire and a plane, and of a wire and a cylinder, a decided rectifying effect was discernible in the space about the conductor in corona, in that that region was built up to a unidirectional potential above ground, the magnitude and polarity of this potential depending on the voltage applied. In both of these set-ups, this net rectification, which is evidently caused by some differential action entering into the ionization process, was of a positive sign at the start of corona, but changed over to negative as the voltage was raised.

In a test made on two 1.1-in. diameter, parallel concentric strand copper conductors, 10 ft. apart, the space between them was found to have assumed a potential above ground when the conductors were in corona, the sign of this charge being negative at first, and then positive as the voltage increased. Tests were also carried out on a single brush, and on a rod fitted with "artificial" brushes.

In a corona-loss curve taken on the two cable conductors it was found that at the same voltage at which the sign of the rectified space charge had reversed, there was a "break" in the curve. This "break" corresponded to the point above which Peek's quadratic law of corona holds, and below which he has suggested the entrance of a probability relation.

A final field test was made at a span of the 220-kv. Pit River Lines of the Pacific Gas and Electric Co., in order to ascertain the magnitude and polarity of the charge built up about a high-voltage line in service. A negative polarity was found to be present as far down as 30 ft. below the conductors. Although the voltage was raised to 260 kv., the charge remained negative, indicating that the line at its normal 220-kv. potential was operating at a point on the corona-loss curve appreciably below that where the break occurs in the curve.

General Experimental Study of Space Charge

THE continuation of the study of the nature of the space charge that surrounds a conductor in corona was made during the past year in the Ryan High-Voltage Laboratory by attacking the problem from several different angles.[7]

One of the simplest cases giving evidence of the presence of a space charge is in the time-honored set-up of the wire at the center of a cylinder. If the cylinder is connected to ground through a condenser and a d-c. galvanometer is shunted across the condenser and then alternating voltage is applied to the wire at the center of the cylinder, the galvanometer will indicate, in the usual set-up, the presence of a unidirectional current as soon as corona appears on the wire[3]. If the galvanometer shows a deflection, it indicates that some of the space charge that is planted about the conductor is getting over to the cylinder. Since the sign of the charge leaving the conductor reverses each time the voltage reverses, the deflection of the galvanometer indicates that charges of only one sign get over to the cylinder or that more of one sign than the other gets over. With the ordinary set-up, this unidirectional current is usually from the cylinder to ground at first but as the voltage is raised the galvanometer indicates a reversal of current. The reason for this will be taken up later.

If the wire and cylinder be replaced by a wire and neutral plane, the circuit connections being the same as those described in the use of the cylinder, the results obtained will be similar.

A little more as to the nature of the space charge can be learned by the set-up shown in Fig. 1. This method has been used by several others in the past and is not given here as anything new, but only to complete the story.[3,4] If, for example, the plate is made positive with respect to the wire mesh, part of the negative ions arriving at the wire mesh will be drawn through to the plate where they will give up their charge which will then produce a deflection of the galvanometer. The relative amount of the space charge arriving at the neutral plane can be observed under different conditions with respect to voltage, size of wire, distance of wire from

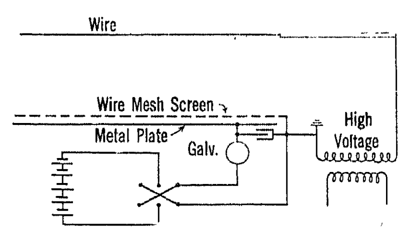

Fig. 1

plate, etc. A great deal of work has been done along this line by Mr. Willis.[4] A characteristic plot of results that were obtained by the authors using the method just described is given in Fig. 2. The curves show that the positive ions reach the neutral plane at a lower applied voltage on the wire than do the negative ions. The number of negative ions reaching the neutral plane, however, increases more rapidly with an increase in applied voltage than does the number of positive ions. If it were not for the fact that a single brush from a point has almost the same characteristic curves as those

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7. See Bibliography for reference.

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see Jl. A.I.E.E. Dec 1927 pp 1350 to 1357

in Fig. 2, except with reverse polarity, it might not be so difficult to offer an explanation for the form of these two curves. If high-voltage direct current is applied to the wire instead of alternating current, and the corona current plotted against the applied voltage with the wire positive and then with the wire negative, the results will not differ much in form from those shown in Fig. 2.[5] Three of the factors that help to determine the form of these curves are the mobilities of the ions, their rate of manufacture and the amount that their presence disturbs the normal field.

One of the most important things is lacking in the results obtained by means of the set-up shown in Fig. 1 and that is the time element. In other words, what is the wave form of the current produced by the arrival of this space charge at the neutral plane? Since the action is cyclic, it was a comparatively easy matter to determine the form of this wave. The set-up shown in Fig. 3 was evolved. The principle made use of here is very simple: If a charged electroscope is brought near to a conductor in corona, it will be discharged, of course, by the attraction of the ions which will neutralize its charge. Now suppose instead of exposing the electroscope continuously, a synchronous shutter be provided that will expose it for only a certain portion of the cycle. If the rate of discharge of the electroscope be noted as the shutter is operated at different phase angles with respect to the applied voltage, the determination of the wave form can be made. This synchronous shutter arrangement was obtained by means of a four-pole synchronous motor driving a 12-in. aluminum disk with two radial slots 3.5 in. long and five deg. wide; see Fig. 3. This disk rotated under a metal plate in which there was a slot the same size as those in the disk and the position of the disk was such that the slot in the plate and a slot in the disk came in line once each cycle. When these slots coincided, the plate of the charged electroscope could draw through some of the ions that arrived at the metal plate, thereby discharging the electroscope. The rate of the discharge of the electroscope is a measure of the relative number of ions arriving at the neutral plane at that instant. The phase angle of the motor driving the disk was changed by means of a phase shifter and in this way the action over a complete cycle could be observed with the electroscope charged positively and then with it charged negatively. The electroscope was charged after each reading by means of a well-insulated switch, S_1. A 1050-kv-a., 60-cycle, sine wave

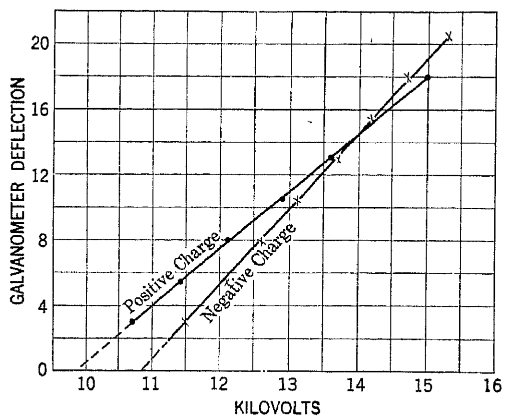

FIG. 2—CURVES SHOWING THE AMOUNT OF POSITIVE AND NEGATIVE CHARGE ARRIVING AT THE NEUTRAL PLANE IN RELATION TO THE APPLIED VOLTAGE. A NO. 14 POLISHED COPPER WIRE 5.5 IN. FROM NEUTRAL PLANE.

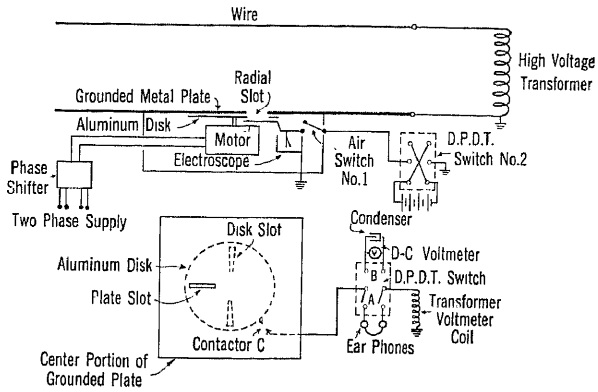

FIG. 3

generator was used in this work. To determine the phase position of the synchronous disk with respect to the applied voltage, a contactor C was arranged on the disk so that it closed a circuit at the instant when the slot in the disk and the slot in the plate lined up. With switch No. 2 closed in the A position, a click could be heard in the phones when the contactor closed the circuit. By shifting the phase angle of the revolving disk, a position on the phase shifter could be found where there was no click, which indicated the zero point of the voltage wave. Since the motor used could

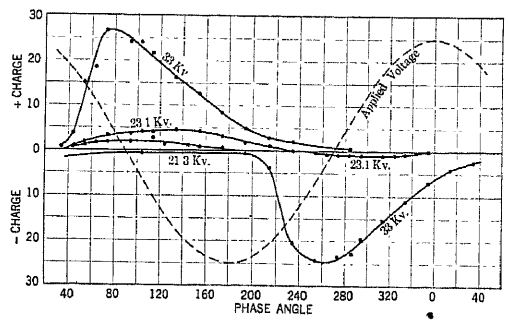

FIG. 4—CURVES SHOWING THE RELATIVE AMOUNT OF CHARGE ARRIVING AT THE NEUTRAL PLANE AT THE VARIOUS PHASES OF THE VOLTAGE CYCLE. A NO. 14 POLISHED COPPER WIRE 5.5 IN. FROM THE NEUTRAL PLANE

come into step with the disk in one of two phase positions, 180 deg. apart, it was necessary to be certain that this phase was the same each time the motor was started up. To do this, switch No. 2 was closed in B position and with the phase shifter at the same angle each time the motor was made to come into step so that the d-c. voltmeter read positive.

The results obtained by this method are qualitative only but they give additional information that cannot be secured otherwise. Curves shown in Figs. 4, 5, and 6 were obtained by means of this set-up and will be discussed later.

Since the field about a wire above a neutral plane is not symmetrical, it was decided to find out what the

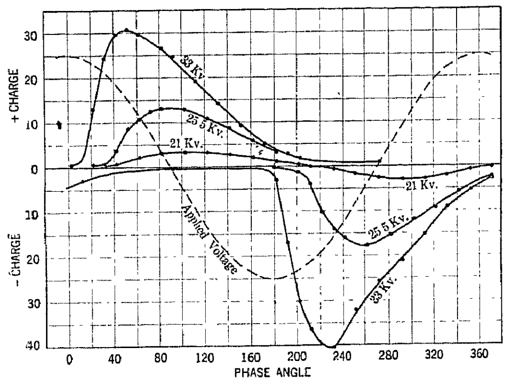

FIG. 5—THE SAME AS FIG. 4 EXCEPT THE WIRE HAD BEEN OUT IN THE WEATHER FOR TWO YEARS WHICH HAD OXIDIZED ITS SURFACE

effect on the form of the curves would be of a uniform radial field. The metal plate was replaced, therefore, by a 15-in. diameter metal cylinder having in it a slot which occupied the same position over the disk as the slot of the metal plate. The data for the curves shown in Figs. 7, 8, and 9 were then taken.

The curves of Figs. 4 to 9 show that, except for magnitude, there is very little difference in the form of the

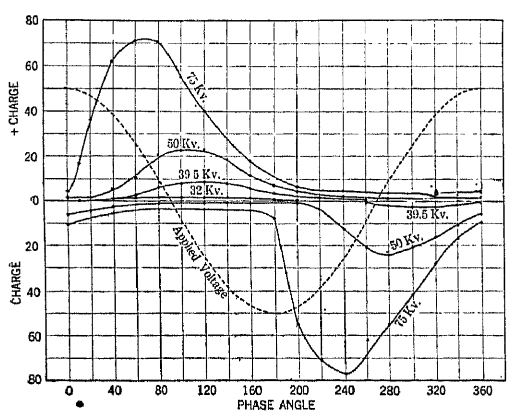

FIG. 6—THE SAME AS FIG. 4 EXCEPT A NO. 10 POLISHED ALUMINUM WIRE WAS USED; ITS DISTANCE FROM THE NEUTRAL PLANE WAS 10 IN.

positive and negative halves of the wave. A very important thing to note is the arrival of the charge at the neutral plane or cylinder sometime after the voltage on the wire has reversed.

There are two fields involved in the drive of the ions across the space, that of the wire itself and that due to the space charge, and the results have shown the latter field to be of considerable importance. In Figs. 4, 5, and 6, the positive charge continues to arrive at the grounded plate even after the voltage on the wire has reversed and reached its negative crest. This is also true for the negative charge and may be attributed to the diffused state of the ions caused by the unsymmetrical field between wire and plane. In the case of the cylinder where the field is radial, there is little or no time when there are ions of both signs present at the

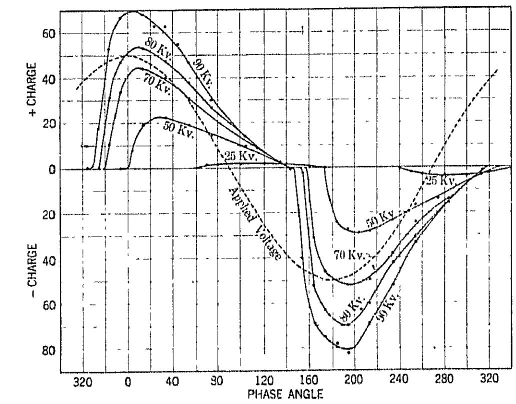

FIG. 7—THE SAME AS IN FIG. 4 EXCEPT FOR A NO. 16 POLISHED COPPER WIRE AT THE CENTER OF A 15-IN. CYLINDER

same instant during the cycle. Figs. 4 and 5 show the difference between a polished wire and one covered with oxide. The positive and negative charges seem to come in at approximately the same voltages with the oxidized wire. An enameled wire was tried also and the curves were similar to those for the oxidized wire. Had a curve been taken at a little higher voltage with the polished wire, the negative charge would have

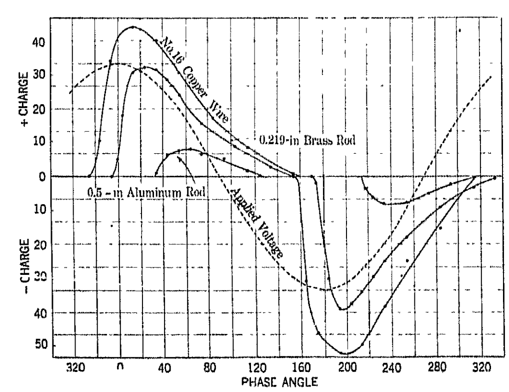

FIG. 8—CONDUCTORS OF DIFFERENT DIAMETERS AT THE CENTER OF A 15-IN. CYLINDER. APPLIED VOLTAGE HELD CONSTANT FOR ALL THREE AT 70 KV.

exceeded the positive as it did in the case shown in Fig. 6.

(Since the scale used for plotting the flow of charge was dependent upon the rate of fall of the leaf of the electroscope, which in turn was dependent upon the position and calibration of the electroscope, the only quantitative comparison of curves that can be made is: Fig. 4 with respect to Fig. 5 and Fig. 7 with respect to Fig. 8.)

It was found that curves obtained with a polished copper wire were practically identical with those secured with a polished aluminum wire of the same size under similar conditions.

In Fig. 9, with the kenotron in the wire circuit, the increase in the flow of charge is to be noted as the voltage on the wire goes over its crest having the same sign as the charge. This increase in the flow of charge is due only to the increase in the field driving the ions across.

Various attempts have been made to compute the movement of ions with conductors in corona. In order to do this, some have assumed varying mobilities for the ions which in our opinion is not justifiable until more data concerning the nature of this space charge are available.

If the distance from the wire to the grounded plane or cylinder be made sufficient, charges of both signs will not get across, but in no case in our tests was the distance so great that none of the charge of either sign got over when corona was present on the conductor.

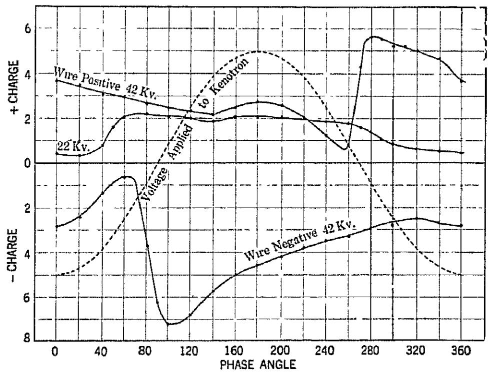

Fig. 9—Same as in Fig. 7 Except Voltage was Applied to the Wire Through a Kenotron

In fact, charges were found 30 ft. out from a conductor of a 220-kv. commercial power line on which there was but slight corona. This test will be discussed more fully later.

For a limited space about a conductor in corona, the sign of the charge is reversed at each reversal of voltage. Beyond this space, charges of only one sign appear, which fact is undoubtedly due to a differential effect of the alternating charge near the conductor. The polarity of this charge is not the same for all conditions. In general, with an unpolished conductor out in the open, such as a transmission cable, the charge is negative at the first appearance of corona but as the voltage is raised it changes over to positive. If the wire is highly polished and near the neutral plane, however, the charge is positive at first and then negative. If the distance to the ground electrode is relatively great, the actual flow of rectified current to supply this outer charge is very small. In some cases, however, the potentials built up by the charges are fairly great.

If in the case of the wire and cylinder some method is used to neutralize or balance out the charging current from the cylinder to ground that would flow if corona were not present, the current that remains is commonly called the corona current. The latter is made up of two elements; namely, the ions that actually reach the cylinder and the bound charge that is drawn to the cylinder by the ions that leave the wire but do not get

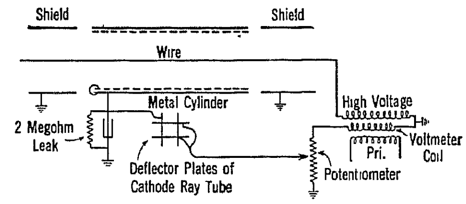

Fig. 10

across. The question arose here as to what percentage of this current was due to the ions that arrived at the cylinder. The set-up in Fig. 10 was used to obtain the corona current. Below the corona starting voltage, a position was found on the potentiometer control such that there was no deflection of the cathode ray. This point, once found, would be the same for all voltages, so that when corona came in, the deflection of the cathode ray would be due to the voltage across the condenser, caused by the corona current only. The value of this voltage was determined from the amount of deflection of the cathode ray, and with the capacitance of the condenser known, the average value of the corona current was computed. The set-up in Fig. 11 was next used to determine the current produced by the ions actually reaching the cylinder. The principle is the same as that shown in Fig. 1. In this case, however, it was necessary to trap all the ions reaching the center section of the cylinder; therefore, a wire cylinder of ¼-in. mesh was fitted inside of the sheet metal cylinder with eighth-in. hard rubber strips separating the two. The main difficulty with this set-up was involved in completely separating the positive and negative ions.

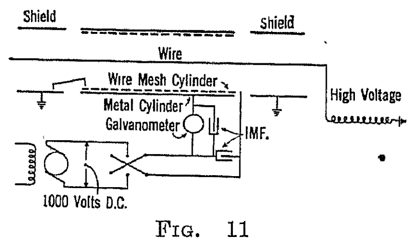

Fig. 11

With the a-c. voltage held constant on the wire, which was in corona, the d-c. voltage applied to the sheet metal cylinder was increased in steps from zero to 1000 volts and galvanometer readings were taken for each voltage. It was hoped that a plot of these values would give a saturation curve indicating a complete separation of the positive and negative ions, but this was not found possible in this case. A wire screen

with smaller mesh was also tried but was even less effective. Using the average value of the current, however, as read by means of the galvanometer, when there was 1000-volt direct current on the metal cylinder, it was found in the case of the 0.219-in. brass rod with voltages above 50 kv., at least 70 per cent of the ions that left the wire reached the cylinder before they were drawn back to the wire by the reversal of voltage or were neutralized by the outgoing ions of the opposite sign. With a little modification in this set-up, there is no reason why a complete determination of this ratio could not be made.

Since the corona on a transmission conductor is made up largely, if not entirely, of brushes, a point was placed on the side of the 0.219-in. brass rod in the cylinder and the corona current studied with set-up of Fig. 11. At the first appearance of corona at 11 kv., the charge arriving at the cylinder was negative and remained negative until the positive began to get across at 40 kv. From 40 kv. to 48 kv., there was more positive than negative reaching the cylinder but from 48 kv. up to the flashover voltage the amount of the negative exceeded the positive. The point used was a piece of fine wire 1/16 in. long. The rod was then tried with two such points and it was found that the negative charge arriving at the cylinder always exceeded the positive, although it decreased slightly from 43 kv. to 45 kv.

Space Charge Surrounding Transmission Conductors

The ionization about transmission conductors was next studied. Two concentric strand copper cables 1.1 in. in diameter and 50 ft. long were strung up in the laboratory parallel to each other and 10 ft. apart with a clearance of at least 20 ft. in all directions. A No. 16 wire was supported parallel to, and midway between, the two conductors. Hard rubber rods were used for insulators on this test wire and a lead from it was brought out at right angles to the plane of the two large conductors. An electroscope was connected between the test wire and ground and voltage was then applied to the two conductors. Below the corona voltage, the test wire was adjusted so that the electroscope showed no voltage on it due to position in the electrostatic field which indicated that it was in the neutral plane. The voltage was raised and at the first appearance of corona at 160 kv. between lines the electroscope showed a negative charge on the test wire. The negative potential increased on this wire as the applied voltage was raised until at 280 kv. between lines it was approximately 3000 volts. As the applied voltage was further raised, the potential on this test wire started to fall, slowly at first, then more rapidly, until at 300 kv. between lines it reached zero and then began to build up positive. At 500 kv. between lines the test wire had a positive potential of approximately 15,000 volts above ground. It was necessary to parallel the electroscope with a condenser to obtain the d-c. charge on the test wire when the applied voltage on the conductors was above 300 kv. Another test that was made with this set-up was to short-circuit the electroscope until the voltage had been taken off the large conductors and then the short circuit was removed. When this was done at 280 kv. the test wire accumulated sufficient

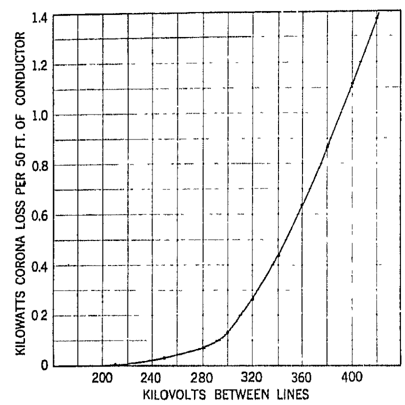

Fig. 12—Corona Loss Curve for a 1.1-In. Concentric Strand Copper Conductor. Distance Between Conductors, 10 ft. Insulator Losses Are Not Included

negative charge to raise potential of the test wire several hundred volts. The same thing was tried at 400 kv. In this case, the potential on the test wire was over a thousand volts positive. These potentials were due to the persistence of the charge about the conductors after the source of ionization had been removed. In some cases, charges were found to build up potentials of a few hundred volts on the test wire as long as fifteen minutes after the voltage had been removed from the conductors.

A corona loss curve was then taken and is shown in Fig. 12. It is rather interesting to note that at 300 kv. between lines there is a break in the loss curve, and it is at this point that the potential of the charge about the conductors changes over from negative to positive.

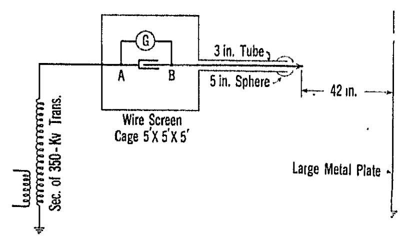

Fig. 13

Above this point, Peek's quadratic law seems to hold, but below, it does not, and it is in this lower region that Peek has suggested a probability law.[6]

Since the corona on these transmission cables appeared to be made up of individual brushes, it was decided to study the characteristics of a single brush. The set-up shown in Fig. 13 was used. An observer in the insulated screen cage at high voltage took all the

necessary data. With this arrangement, the capacitance of the metal point is practically zero, so that the only current flow to and from the point is corona current. The simple connection of the condenser and galvanometer was the first one used. At the start of corona from the point which appeared as a soft glow,

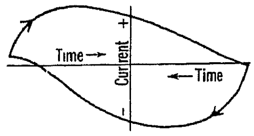

FIG. 14—CORONA CURRENT CYCLOGRAM OF A BRUSH FROM A SINGLE POINT. VOLTAGE 100 KV. 100,000-OHM SHUNT FOR CURRENT DEFLECTORS AND 9400-OHM SHUNT FOR TIMING VOLTAGE

the galvanometer indicated a flow of negative current which increased until at 112 kv. the galvanometer deflection was two divisions. At this voltage, purplish streamers began to shoot out which considerably increased the luminosity of the brush. At 132 kv. the galvanometer had fallen to zero and at 140 kv. the current was positive, giving a deflection of two divisions. By this time the purple streamers had greatly increased and at 172 kv. the discharge was a large, well-developed brush giving a reading on the galvanometer of 10 divisions positive. The condenser and galvanometer were then replaced by the cathode ray tube. A 100,000-ohm resistance connected between the points A and B gave sufficient voltage drop to obtain a good deflection of the cathode ray that was proportional to the current. This current deflection was opened out into a current cyclogram by applying a sine wave voltage to the other pair of deflector plates. This sine wave voltage was obtained from a 2300-volt exciting winding connected to the high-voltage end of the secondary. This voltage had been tested and found to be a sine wave in phase with the secondary voltage. In order to put the important changes of current intensity in an advantageous position on the cyclogram for analysis, the phase angle of this timing voltage was shifted 90 deg. by means of a condenser. In the cyclograms shown in Figs. 14 and 15, the corona current appears to be a maximum shortly before the timing voltage impressed on the tube is zero, but due to the 90-deg. shift it can be seen that the maximum of the corona current is approximately 25 deg. ahead of the maximum of the voltage applied to the point. The form of these corona cyclograms would be altered slightly if they were changed over to a uniform time axis instead of the sinusoidal timing wave. The direction of rotation of the spot that traced these curves was carefully checked, as was also the polarity of the cathode ray tube deflectors. In Fig. 14, the positive and negative halves of the current wave are smooth and are practically the same. In Fig. 15 the negative side is still smooth but the positive side shows a sudden pulse of current. It was difficult to get the exact form of this pulse because the rapid movement of the spot did not leave a very distinct trace. Simultaneous with the appearance of this pulse of positive current, as the form changed from that shown in Fig. 14 to the one shown in Fig. 15, was the appearance of the long purple streamers. When a half-in. brass sphere was put over the end of the point, breaks appeared in the negative half of the current wave but they were not so prominent as those on the positive side. Time nor space does not permit much more to be said about these tests with the single brush. More work is to be done along these lines and a complete report will no doubt be made later.

Current cyclograms were taken on the 1.1-in. transmission conductor previously mentioned with the charging current balanced out. While they were not so clear cut as those of the brush from the single point, they had the same general form. If all the brushes on the transmission conductor came in at the same voltage, the result, of course, would be practically the same as the brush from the single point except for magnitude. This is very nearly the case when voltage is not far above the corona starting voltage when there are only a few brushes present. Since this is within the economical range, the region we are most interested in, the authors believe that much can be learned about the mechanism of corona about the transmission line by the study of the brush from a single point. It is also their belief that results obtained from polished smooth surface conductors, especially if they are mounted near a neutral plane, are not applicable to transmission lines out in the open.

TESTS MADE UNDER A 220-KV. TRANSMISSION LINE

In order to tie in the results obtained in the laboratory with those of actual operating conditions, the authors

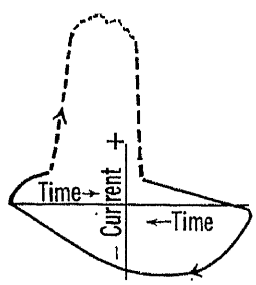

FIG. 15—SAME AS FIG. 14 EXCEPT 130 KV. AND 40,000 OHMS FOR CURRENT SHUNT AND 4900 OHMS FOR TIMING VOLTAGE SHUNT

went to the 220-kv. lines of the Pacific Gas and Electric Co. at the Vaca-Dixon substation. The section under which the tests were made was that of a three-phase, 220-kv. line with 0.9-in. ropelay copper conductors in the horizontal configuration. The separation of the conductors was about 14 ft. and they were approximately 63 ft. above

the ground. At right angles to these conductors and 30 ft. under them, an exploring wire 33 ft. long was supported by hard rubber rods on long cotton cords. A lead was brought down from the exploring wire and connected to one side of a gold leaf electroscope the other side of which was connected to ground. In order to reduce the a-c. voltage due to position, the electroscope was paralleled by a 0.05 μ f. condenser the leakage of which was negligible. At first, a d-c. potential of 400 volts was applied to the wire which at the same time charged the condenser. The d-c. source was then removed and the rate of decrease of voltage on the condenser was observed by the fall of the leaf of the electroscope. With a positive charge on the wire, the voltage of the condenser dropped from 400 to 375 volts in three min. With the wire charged negative, there was no decrease in the condenser voltage for the same length of time. It was obvious then that there were only negative ions present in the vicinity of the exploring wire. This was the condition that was expected to be found in view of the results obtained in the previous laboratory tests. With no charge on the wire, the set-up was left untouched for an hour. At the end of this time the wire had picked up sufficient charge to raise the voltage on the condenser to 305 volts. The charge on the condenser was tested and found to be negative. It was observed that when a rather strong breeze was blowing, the ionization about the wire decreased considerably. This was to be expected with distances from the conductor as great as these.

The voltage was then taken off the section of line above the set-up and the exploring wire was raised until it was within 15 ft. of the conductors. The voltage was then supplied to this section of the line by means of a 40,000-kv-a. synchronous condenser driven by an induction motor. In this way the voltage applied to the line could be varied. Observations were made at three different voltages, 220 kv., 240 kv., and 260 kv. The main purpose of this test was to see if the normal operating voltage was near the value where the residual charge in the atmosphere about the conductor changed from negative to positive. At 260 kv. there was no evidence of any positive charge in the near vicinity of the exploring wire which was 15 ft. from the conductors. The amount of negative charge was found to be slightly greater than it was at 220 kv. with the exploring wire 30 ft. below the conductors.

Acknowledgment

The authors greatly appreciate the generous cooperation of the Pacific Gas and Electric Co. and they are particularly indebted to H. F. Flynn and his assistants at the Vaca-Dixon substation for their invaluable aid in carrying out the test there.

Summary and Conclusions

In the ionization process about a conductor or electrode in corona, there is a net rectifying action present whereby more charges of one sign assert themselves than of the other, so that the surrounding space is built up to a unidirectional potential above ground. Whether it is a case of the charges of the predominating sign being created more rapidly, or whether they endure longer than the others without being "wiped out" by recombination or return to the conducting circuit of the set-up, is not known, as it is apparently a part of the mechanism of ionization involved. It is probably determined by the mobilities of the ions, their rate of manufacture, and the amount that their presence disturbs the normal field.

For a given test arrangement, the magnitude and polarity of this rectified charge is dependent on the applied voltage. For the case of a polished wire and a grounded plane or cylinder, the sign of this charge is first positive, but soon drops to zero and then increases negatively as the voltage is raised. By placing a small "artificial" brush on the wire, it was possible to detect a slight negative rectification at the start of corona from it. The sign soon reversed, though, to positive as the voltage increased, and then to negative once more where it remained until flashover.

In a test with a single point projecting from a small sphere, the rectified space charge built up was first negative and then positive. The same was found to be true in the space between two 1.1-in. diameter cable conductors strung up in the laboratory. This would be expected since the corona on the surfaces of the stranded conductors would be, in reality, a mass of small single brushes, so that as a whole they would assume the characteristics of a single brush.

The fact that at the same voltage on the cable conductors at which the rectification of the charge reversed its polarity from negative to positive, there is a distinct "break" in the corresponding corona loss curve, proved of considerable interest. Since it is at this point that Peek's quadratic law relation begins to hold, it would seem from these tests that there is some governing factor contributed coincident with positive rectification to cause the ionization process to vary quadratically with respect to applied voltage. It is this upper portion of the curve that Dr. Ryan has referred to as that of "stable brush pattern." The lower portion he has called that of "unstable brush pattern," and it is here that Peek has suggested the entrance of a probability relation.

In the field test made on the 220-kv. Pit River Line of the Pacific Gas and Electric Company, which normally shows slight visible and audible signs of corona, it was apparent that the line was being operated at a point well below the "break" in the corona loss curve, as the space about the conductors was found to be charged negatively even when the voltage had been raised 20 per cent above the normal line voltage. Although the potential of the rectified charge is appre-

ciable, the actual magnitude of the current necessary to supply it is negligible compared to the alternating space charge current itself.

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Discussion

L. F. Fuller: It has been my privilege to discuss this work with the authors frequently during its progress and I have been impressed continually with the difficulty of the undertaking and the fact that it is pioneer work at the very forefront of our knowledge of things of this character.

Already it has had a very practical application of which I wish to tell you.

Several years ago it was observed that if a carrier-current telephone transmitter and receiver were connected at each end of a high-voltage transmission line in corona, a noisy, hissy sound was observed in the receiver whenever the carrier transmitter was started. The intensity of this noise increased with the power of the transmitter. This resulted in a noisy background to any speech transmitted over the line. No advantage could be gained by increasing the power of the transmitter because this increased the received signal and noise together, and the signal-noise ratio was not appreciably altered.

The reasons for this phenomenon appear to be closely related to the investigations of the authors. Within the radius of the space-charge cylinder surrounding each line conductor in corona, the ionization is much higher than in the space between conductors outside this radius. The atoms within the cylinder are in a decidedly turbulent condition and the conductivity is relatively high. Any radio-frequency current being passed between a coupling wire and line conductor must pass through this highly ionized region. The coupling wire and the line conductor associated with it do not form a condenser alone but rather a condenser in series with a microphonic rapidly changing resistor comprising the space-charge cylinder. The outer surface of this cylinder and the coupling wire may be considered as comprising the two plates of a condenser. Charging current through this condenser can reach the line conductor only by passing through this variable resistance. Thus the carrier is modulated by the variations of this series resistance and the typical hissing sound is heard in the receiver.

Some time ago Dr. Ryan in discussing space charge with me expressed the opinion that the substitution of coupling capacitors for coupling wires would thereby provide a metallic conductor in place of the variable resistor comprising the space-charge cylinder. This he thought might result in the elimination of the series modulation of the carrier and would remove the disagreeable hiss.

It is with a great deal of pleasure that I am able to report that this desirable result has been very thoroughly proved. Thus we have a practical example of the utility of space-charge studies of this character.

R. J. C. Wood: I didn't quite gather from the paper whether the voltage observed on the electroscope showed the natural gradient which would be in the air at that height whether the transmission line was there or not, or whether it showed as a resultant of the natural gradient and the voltage on the line, or whether it was due to the line alone.

In the first case the coupling rod was 30 ft. above the ground; in the second case it was 45 ft. above the ground; and with those heights above the ground one would expect a certain natural potential different to ground.

C. H. Willis: (communicated after adjournment) The evidence so far obtained regarding the diffused space charge which the authors found at some distance from the corona wires shows this charge to be quite erratic. However, I should like to ask if the authors think it possible that the sign of this diffused space charge at voltages slightly above the corona voltage, may not be determined by the sign of the corona which form at the lowest voltage, and therefore probably is produced in the greatest quantity at voltages a little above the corona voltage.

The curves shown in Figs. 4 to 9 inclusive give valuable information. The great lag of the space charge behind the electrostatic field shown particularly in Fig. 6 is surprising.

The break shown in the loss curve of Fig. 12 comes at about the voltage at which we should expect the two alternating space charges from opposite wires to meet as calculated from the mobility which has been found for ions in corona. When the two alternating space charges do meet the phenomenon changes to a case of gaseous conduction and it is to be expected that the loss curve will obey a different law. It would be quite interesting if this break could be shown to depend on the distance between the wires.

J. S. Carroll: Professor Reukema in his paper shows the short time required to clear the ions out of the space between the two spheres of a sphere-gap when 60-cycle voltage is used. In this case there is little chance of studying the movement of the ions. However, if the ions are supplied by one of the electrodes being in corona, such as a point or a small wire, the movement of the charge plays quite a different part. In that regard I should like to call attention to a few things brought out by the results shown in the curve of Fig. 9, in the paper by Lusignan and myself.

The voltage was applied to the wire at the center of a grounded cylinder by means of a kenotron connected to a high-voltage transformer. This voltage was of course unidirectional and pulsating. At a phase angle of 180 deg. the voltage applied to the wire is a maximum. No doubt the wire went into corona before this, but it is not until about a quarter of a cycle later that the charge sent out by this pulse of voltage gets over to the cylinder. The charge continues to arrive at the cylinder after this pulse gets across but gradually decreases in amount until at 270 deg. it is almost zero. Had the cycle been longer, that is the frequency a little lower, all the charge sent out at this voltage crest would have got across before the next pulse arrived.

It is interesting to note the slight increase in the amount of charge getting over at 180 deg. This is no doubt due to the increase in the resultant field caused by the rise in voltage applied to the wire. By resultant field I mean the field set up by the voltage applied between the wire and cylinder plus the field existing between the space charge and cylinder. This latter field is a very important factor in determining the movement of the ions in this and similar setups, so that it is very difficult to calculate ionic movements when a good part of the field that is producing this movement is attached to the moving ions themselves.

J. T. Lusignan, Jr.: Mr. Wood brings up the question as to how much of the unidirectional voltage which we measured beneath the outdoor transmission line was due to the natural gradient or the earth. Probably very little was involved as we got no detectable reading on the electroscope when the line voltage was off. Also we found the electroscope readings to increase as the potential of the line was raised. Our motive in making the test under a transmission line was prompted by the fact that we had found a unidirectional potential about conduc-

tors inside the laboratory where the earth's field would have no effect.

J. S. Carroll: Mr. Willis' question regarding the sign of this diffused space charge is not quite clear.

In order to determine the sign of the charge in the way suggested by Mr. Willis one would have to specify very carefully the conditions under which it would hold. For instance under certain cases the charges about polished conductors have opposite signs to those with rough conductors at the same impressed voltage.

Electric Oscillations in the Double-Circuit Three-Phase Transmission Line*

BY Y. SATOH[1]

Enrolled Student, A. I. E. E.

***Synopsis.**—This paper, after referring to the results of a previous study of the electric oscillations on the three-phase aerial line obtained by Dr. Bekku, describes the additional work done by the writer concerning the electric oscillations in the double-circuit, three-phase transmission line, and shows that there are three kinds of traveling waves. The nature of these waves, and some of the important results of the induced transients, are described. In the appendixes, it is shown briefly how these results were derived and how to calculate the line constants from the construction data of the lines. A few numerical examples are given.*

IN 1923, Dr. S. Bekku deduced the theory of electric oscillations in the three-phase aerial line[2] and showed that, when the three phases are symmetrical, there arise two kinds of traveling waves having different surge impedances and, in general, different propagation velocities. He showed also that when the conductivity of earth is infinity, the propagation velocities of the two waves become equal to that of light.

Referring to his paper, the writer has discussed the oscillations in the double-circuit, three-phase transmission line which are of practical interest and has pointed out some of the important points obtained in studies of these oscillations.

NATURE OF WAVES ON THE SINGLE- AND DOUBLE-CIRCUIT LINES

When a single conductor is running parallel to a boundary plane of a perfect conductor, the oscillation therein as is well known, consists of one kind of traveling wave having a propagation velocity equal to that of light. If, however, several conductors closely parallel one another, as in the case of ordinary transmission lines, there exist various kinds of traveling waves, due to mutual inductive effects. It was shown in Dr. Bekku's paper that in the three-phase line, if the three conductors are balanced, *i. e.*, if the transposition is complete, there are two varieties formed and there are two kinds of traveling waves. The first kind has currents and voltages the sums of which in the three conductors are zero, while the currents and voltages of the second are equal for three conductors. The first is a wave between conductors and the second is a wave between the group of conductors as one side and the ground as the other. The same theory applies to both aerial lines and underground cables.

*With supplementary discussion by H. G. Brinton.

1. Graduate student, Stanford University.
2. *Jl. of Japanese Inst. of E. E.*, Feb., 1923.

Presented at the Pacific Coast Convention of the A. I. E. E., Del Monte, Calif., Sept. 13-16, 1927.

See Apr 1927 MEGJE. ~~pp 868-877~~ 868-877

If another three-phase circuit of the same electrical characteristics is closely coupled to the former circuit, as in the case of ordinary double-circuit, three-phase power lines, and if we assume that each conductor of one circuit is in the same position with respect to the conductors of the other circuit, then the oscillations therein are the superposition of three kinds of traveling waves, as follows: (The above assumption is not satisfied unless a special method of transposition is used, however, according to the numerical calculations for the actual lines, the assumed conditions are practically realized.)

1. The wave whose sums in voltages to ground and currents of the three conductors of each circuit are zero.
2. The wave whose voltages to ground and currents are equal for all of the six conductors.
3. The wave whose voltages to ground and currents are equal for the three conductors of one circuit and equal but opposite in sign for the three conductors of the other circuit.

Each of the above three kinds consists of two component waves traveling in opposite directions, and each current wave is accompanied by the corresponding voltage wave in the ratio of surge impedance; that is, each kind acts by itself as does the ordinary wave in the case of a single conductor.

The three kinds of waves may be stated as follows:

1. The first kind consists of two waves;
   a. The wave between conductors of the first circuit,
   b. The wave between conductors of the second circuit,
2. The second is the wave between the group of six conductors as one side and the ground as the other side.
3. The third is the wave between the group of three conductors of one circuit as one side and the group of three conductors of the other circuit as the other side. The three kinds are illustrated as in Fig. 1.

Thus we see that a wave can never exist on one conductor only, but it is always accompanied by its companion waves on the other conductors. The surge impedances and the propagation velocities of these waves can be expressed as follows:

For the first kind,

$$Z_1 = \sqrt{(L - L_1)/(K - K_1)}, \qquad (1)$$

$$v_1 = 1/\sqrt{(L - L_1)\,(K - K_1)}, \qquad (\mathbf{1a})$$

For the second kind,

$$Z_2 = \sqrt{(L + 2\,L_1 + 3\,L_2)/(K + 2\,K_1 + 3\,K_2)}, \qquad (2)$$

$$v_2 = 1/\sqrt{(L + 2\,L_1 + 3\,L_2)\,(K + 2\,K_1 + 3\,K_2)} \qquad (\mathbf{2a})$$

For the third kind,

$$Z_2 = \sqrt{(L + 2\,L_1 - 3\,L_2)/(K + 2\,K_1 - 3\,K_2)}, \qquad (3)$$

$$v_2 = 1/\sqrt{(L + 2\,L_1 - 3\,L_2)\,(K + 2\,K_1 - 3\,K_2)} \qquad (\mathbf{3a})$$

in which

L = Self inductance per unit length of a conductor with ground return,

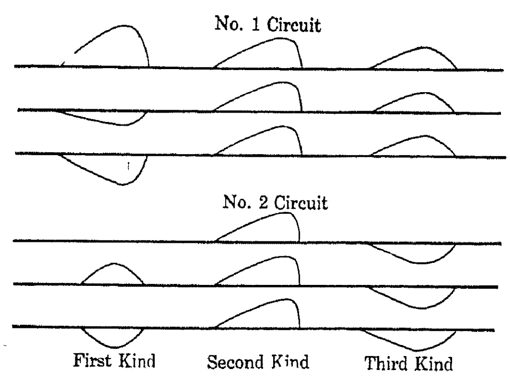

FIG. 1—ILLUSTRATION OF THREE KINDS OF WAVES

L_1 = Mutual inductance per unit length between conductors of the same circuit with ground return.

L_2 = Mutual inductance per unit length between conductors of the different circuits,

K = Coefficient of capacity per unit length of a conductor,

K_1 = Coefficient of static induction per unit length between conductors of the same circuit,

K_2 = Coefficient of static induction per unit length between conductors of the different circuits.

As is clear from the above expressions, the surge impedances and the propagation velocities of the three kinds of waves are different. If the conductivity of the earth is assumed to be infinity, the three velocities become equal to that of light.

The relative magnitudes of the three waves entering into the oscillation are determined by the initial conditions. For example, if equal charges are thrown on the conductors, as might be the case in a lightning stroke, only the second wave comes in. In three-phase switching operations there will exist only the first wave.

REFLECTIONS AND REFRACTIONS

If the waves meet an irregularity, the reflections and refractions occur as in the case of a single conductor. If the irregularity is the same for the six conductors, each kind of wave independently obeys the same laws of reflection and refraction as in the single conductor. If, however, the irregularity is different in the various conductors, interference and splitting-up occurs among the different kinds of waves; *i. e.*, although the incoming wave is one kind, the reflected and refracted waves consist, in general, of three kinds. If the irregularity is the same for the conductors of the same circuit, the first wave acts separately from the other waves, being reflected without splitting-up, while there is splitting-up between the second and the third waves. For example, if the ends of the six conductors are grounded equally through the resistance R, then all waves obey the law, $G = -F\,(R - Z)/(R + Z)$, in which F and G are the incoming and reflecting current waves of one kind and Z is the surge impedance corresponding to that kind. From the above formula, we see that when the six conductors are equally grounded with the resistance equal to the surge impedance of a certain kind of wave, the reflection is zero when the incoming wave is of that kind, but this is not the case for the incidence of the other waves.

When the line having the surge impedances Z_1, Z_2, Z_3, for the three kinds of waves is connected to another double-circuit, three-phase line of surge impedances Z_1', Z_2', Z_3', then

$$G = F\,(Z - Z')/(Z + Z')$$
$$H = F\,.\,2\,Z/(Z + Z')$$

for each kind of waves, in which H is the refracted current wave, that is, H is the current wave that travels on past or through the irregularity.

When the conductors of the same phase of two circuits are tied together at the end of the line, as in the case of a paralleling bus, this end acts as an insulated end for the second wave and as a grounded end for the third wave, while for the first wave, there occurs no reflection; that is, the incoming wave on the first circuit passes through the tie bus and returns on the second circuit and vice versa.

SOME OF THE EFFECTS OF INDUCED TRANSIENTS

From the above results we see that any oscillation in one conductor is always accompanied by corresponding oscillations in the other conductors. If, in the case of a single conductor, the conductor is grounded or broken on the way of the wave, the wave undergoes total reflection and cannot pass through the faulty point. In the case of three-phase lines, however, due to the inductive effects of the sound conductors, the waves do pass through such faulty points. Sound conductors must also stand the high voltage of waves due to induced transients from the nearby faulty conductor. The sound circuit must sometimes stand almost as much voltage as the faulty one. Waves starting on a single-circuit line will induce large transients in a sound circuit that may parallel the faulty circuit, even though the place of fault is some distance away

from the point where the two circuits come together. This will be important because low-voltage lines often parallel high-voltage lines.

Since the sums of currents and voltages of the first and the third waves in six conductors are zero, they do not give inductive disturbances in adjacent lines. Inductive disturbances are caused only by the second kind of wave. The induced voltage resulting from the second kind of wave is obtained by multiplying by six the voltage induced by the individual conductor.

Effect of Losses

Due to the energy losses in the circuits, the waves gradually die out. In this case also each wave acts independently of the other waves and the whole theory obtained for the wave in the case of a single conductor can be applied to the individual wave. For example, each wave has its own attenuation constant and its wave front gradually flattens out just as if the other waves were absent.

Examples

Applying the theory outlined above to several cases one obtains the following results: In these examples, the following values of surge impedances were assumed: $Z_1 = 400$ ohms, for the first wave, $Z_2 = 1000$ ohms, for the second wave, $Z_3 = 500$ ohms, for the third wave. (These are typical values obtained for existing high-voltage lines.) When there is only one three-phase circuit having the same construction as one of the above double-circuit lines, Z_1 is the same as for the double-circuit case, while Z_2 is different and has the typical value $Z_2' = 800$ ohms.

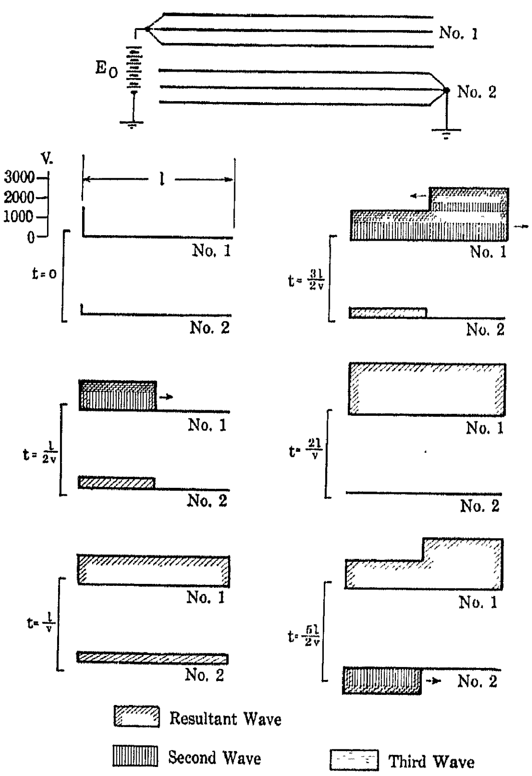

Fig. 2—Voltage Waves of Ex. 1

1. When the voltage source is suddenly connected to one of the circuits having the end conditions as shown in Fig. 2.

The propagation and reflection of voltage waves when the source voltage is 1500 volts d-c. are shown in Fig. 2. The calculation of this example is shown in Appendix III.

In this figure, as well as in those that follow, the different kinds of waves are distinguished by different shadings so far as the clearness of the figures allows. As seen in Fig. 2, two kinds of waves are produced and the voltage wave of 1500 volts on No. 1 circuit is accompanied by the corresponding induced wave on No. 2. When these waves reach the right end, they are reflected. If this end of No. 2 circuit were insulated, or if No. 2 were absent, the maximum voltage in No. 1 would be twice the source voltage, but, affected by the grounding of the right end of the former, the maximum voltage in the latter is 1.8 times. The voltage of 0.85 times the source voltage is induced in No. 2 circuit.

2. When the wave comes from a single circuit. (See Fig. 3.)

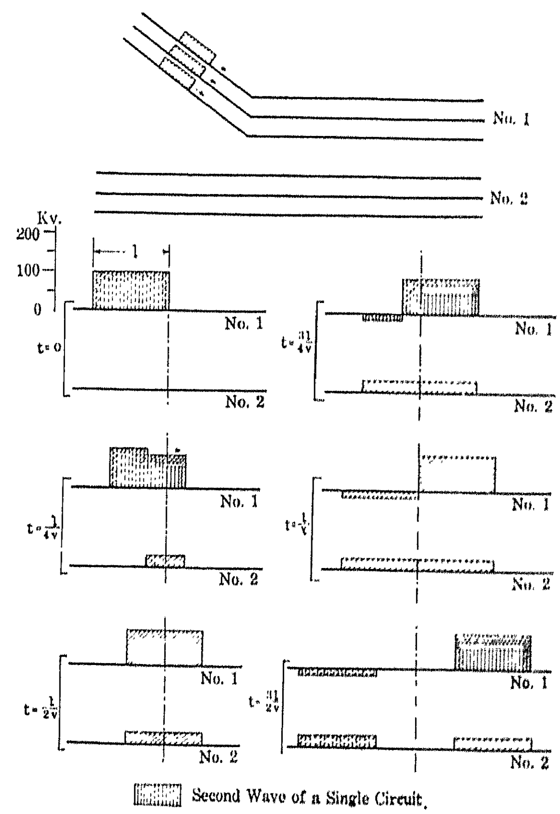

Fig. 3—Voltage Waves of Ex. 2

Fig. 3 shows how the voltage waves split up and give a disturbance in a parallel circuit when waves of 100 kv. between conductors and ground (second kind of wave), come equally on three conductors of a single circuit.

This case might arise from a lightning stroke on No. 1 circuit producing voltage waves that travel to a point where No. 1 parallels with No. 2. If the latter is the low-voltage circuit, the induced voltage may be sufficient to cause a flashover even though the trouble originated in No. 1.

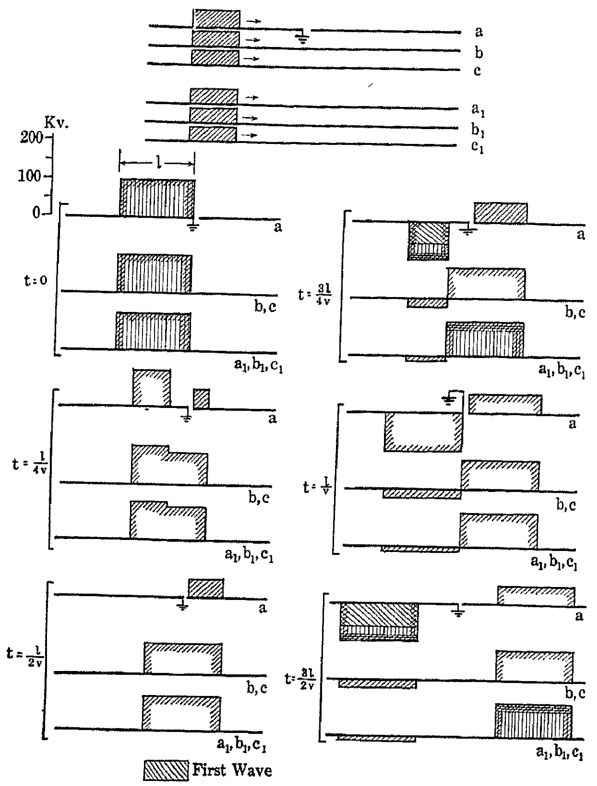

FIG. 4—VOLTAGE WAVES OF EX. 3

3. When one of the conductors is broken and grounded on the way of waves.

The state of reflections and refractions of voltage waves when the incoming wave is of the second kind of 100 kv., is shown in Fig. 4. As shown in Fig. 4, a considerable voltage wave passes the point at which the conductor is broken and grounded due to the inductive effect of the other conductors, and the fault in one of the conductors causes reflections on all of them.

4. When the two circuits are tied together at one end, phases a and a_1 charged to 100 kv., and phases b and b_1, c and c_1 to -50 kv., then the other end of phase a is suddenly grounded, as the result of an insulator failure. (The state of oscillation is shown in Fig. 5.)

An oscillation of this type could arise, if, in the double-circuit lines charged by a three-phase alternator through transformers, the distant end of a conductor is grounded at the instant when the voltage of this phase is maximum. The first few oscillations are represented approximately in Fig. 5 provided the length of the line is not large. This is because the impedances of the transformers are large for the high-frequency oscillation so that the phases may be considered approximately insulated from one another for a short time interval. As seen from Fig. 5, the voltage of 1.8 times the initial value is induced in phases b, c, b_1, and c_1 due to the sudden ground of phase a.

CONCLUSIONS

1. The oscillation in the double-circuit, three-phase transmission line in general consists of three kinds of waves.

2. As the result of the existence of three kinds of waves, there are three kinds of surge impedances.

3. In a single conductor, reflecting waves can be made zero by grounding the end with a resistance equal to the surge impedance of the line. However, when there are three kinds of surge impedances, even if the six conductors are equally grounded with a certain resistance, the reflection may sometimes be zero, or sometimes otherwise.

4. When the waves meet an irregularity of the line, one kind of wave splits up into three kinds.

5. In a single conductor, if the conductor is grounded or broken on the way of traveling waves, total reflection occurs and the waves cannot propagate beyond that point. But, in three-phase lines, due to the inductive effects of the other wires, the waves do propagate beyond the point at which the conductor is grounded or broken.

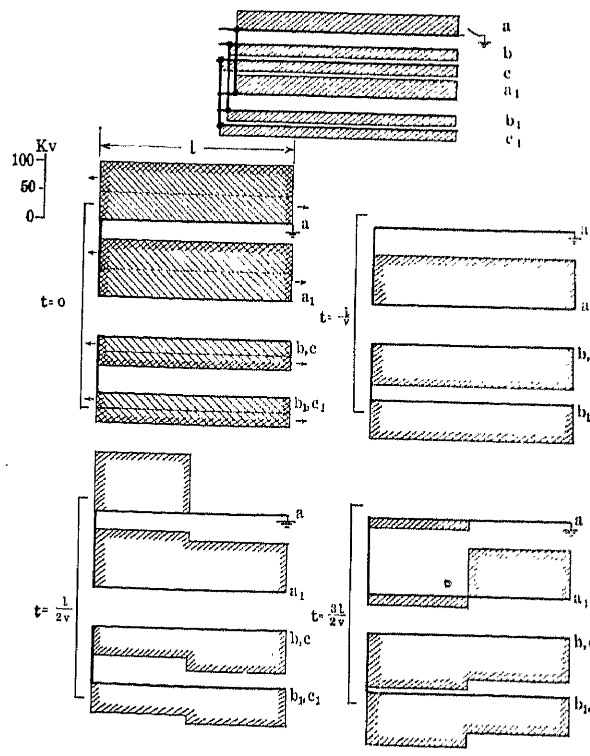

FIG. 5—VOLTAGE WAVES OF EX. 4

6. Due to the fault of one conductor, an appreciable voltage may be induced in the sound conductors; for instance, in example 4, due to the sudden ground of phase a, the voltage of 1.8 times the initial value is induced in the other phases.

7. Inductive interference to neighboring telephone circuits from the transmission lines is caused only by the second kind of wave and can be easily calculated.

The writer wishes to acknowledge the assistance rendered by Dr. F. E. Terman of Stanford University when this paper was prepared.

Appendix I

Derivation of Equations and the Method of Solution

The following assumptions are made:

1. The characteristics of the two circuits are electrically the same.
2. The conductors in each circuit are in the same position with respect to one another and to the ground, *i. e.*, the transposition of each circuit is complete.
3. The conductors in one circuit are in the same position with respect to the conductors in the other circuit.

All the energy losses shall be neglected. Let L, L_1, L_2, K, K_1, and K_2 have the same meanings as in the main text. Let

q = electric charge per unit length of a conductor,
ϕ = magnetic flux interlinkage per unit length of a conductor,
E = voltage to ground of a conductor,
I = current of a conductor,
t = time,
x = distance along the conductor, (take positive directions of x and I the same).

Denote the three conductors of one circuit by a, b, c, and those of the other circuit by a_1, b_1, c_1. Then we have, $\phi_a = L\, I_a + L_1\, I_b + L_1\, I_c + L_2\,(I_{a1} + I_{b1} + I_{c1})$, and if we neglect the voltage drop in earth,

$$-\partial E_a/\partial x = \partial \phi_a/\partial t,$$

or

$$-\frac{\partial E_a}{\partial x} = L\frac{\partial I_a}{\partial t} + L_1\frac{\partial I_b}{\partial t} + L_1\frac{\partial I_c}{\partial t} + L_2\left(\frac{\partial I_{a1}}{\partial t} + \frac{\partial I_{b1}}{\partial t} + \frac{\partial I_{c1}}{\partial t}\right), \tag{4}$$

and exactly similar equations are obtained for conductors b, c, a_1, b_1, c_1.

We have further,

$$q_a = K\,E_a + K_1\,E_b + K_1\,E_c + K_2\,(E_{a1} + E_{b1} + E_{c1}), \tag{5a}$$

and

$$I_a = \frac{\partial}{\partial t}\int q_a\,d\,x,$$

or

$$-\frac{\partial I_a}{\partial x} = \frac{\partial q_a}{\partial t},$$

so that,

$$-\frac{\partial I_a}{\partial x} = K\frac{\partial E_a}{\partial t} + K_1\frac{\partial E_b}{\partial t} + K_1\frac{\partial E_c}{\partial t} + K_2\left(\frac{\partial E_{a1}}{\partial t} + \frac{\partial E_{b1}}{\partial t} + \frac{\partial E_{c1}}{\partial t}\right), \tag{5}$$

and exactly similar equations are obtained for conductors, b, c, a_1, b_1, c_1.

The above equations are the fundamental equations of the electric oscillations in the double-circuit, three-phase transmission line, and since they are twelve simultaneous partial differential equations of the first order and of the first degree having the twelve unknown quantities, I_a, I_b, I_c, I_{a1}, I_{b1}, I_{c1}, E_a, E_b, E_c, E_{a1}, E_{b1}, and E_{c1}, it is seen that their general solutions are twelve indeterminate functions.

To solve the above equations, let us make the following transformations of the variables:

$$\left.\begin{aligned} I_a &= i_a + i_2 + i_3, & I_{a1} &= i_{a1} + i_2 - i_3,\\ I_b &= i_b + i_2 + i_3, & I_{b1} &= i_{b1} + i_2 - i_3,\\ I_c &= i_c + i_2 + i_3, & I_{c1} &= i_{c1} + i_2 - i_3, \end{aligned}\right] \tag{6}$$

$$i_a + i_b + i_c = 0, \qquad i_{a1} + i_{b1} + i_{c1} = 0. \tag{7}$$

$$\left.\begin{aligned} E_a &= e_a + e_2 + e_3, & E_{a1} &= e_{a1} + e_2 - e_3,\\ E_b &= e_b + e_2 + e_3, & E_{b1} &= e_{b1} + e_2 - e_3,\\ E_c &= e_c + e_2 + e_3, & E_{c1} &= e_{c1} + e_2 - e_3, \end{aligned}\right] \tag{8}$$

$$e_a + e_b + e_c = 0, \qquad e_{a1} + e_{b1} + e_{c1} = 0. \tag{9}$$

Though the right-hand sides of the equations (6) and (8) contain 16 variables, since there are 4 relations of (7) and (9) among them, they are essentially 12 independent variables. If these component currents and voltages are known, the currents and voltages of the six conductors are obtained by combining them according to equations (6) and (8). Hence, we shall now obtain these components.

Substitute (6) and (8) into the fundamental equations (4) and (5). By adding all the six equations of (4) and dividing by (6), we get,

$$-\partial e_2/\partial x = (L + 2\,L_1 + 3\,L_2)\,.\,\partial i_2/\partial t, \tag{10}$$

treating (5) the same as above,

$$-\partial i_2/\partial x = (K + 2\,K_1 + 3\,K_2)\,.\,\partial e_2/\partial t. \tag{10a}$$

By adding the three equations of a, b, c of (4) and subtracting from it the three equations of a_1, b_1, c_1, and dividing by 6, we get

$$-\partial e_2/\partial x = (L + 2\,L_1 - 3\,L_2)\,.\,\partial i_3/\partial t, \tag{11}$$

treating (5) the same as above,

$$-\partial i_3/\partial x = (K + 2\,K_1 - 3\,K_2)\,.\,\partial e_3/\partial t. \tag{11a}$$

By subtracting (10) and (11) from the first equation of (4),

$$-\partial e_a/\partial x = (L - L_1)\,.\,\partial i_a/\partial t, \tag{12}$$

by subtracting (10a) and (11a) from the first equation of (5),

$$-\partial i_a/\partial x = (K - K_1)\,.\,\partial e_a/\partial t. \tag{12a}$$

Exactly the same equations as (12) and (12a) are obtained for e_b, i_b . . . . e_{c1}, i_{c1}.

Equations (**10**), (**11**), (**12**,) (**10a**), (**11a**), and (**12a**) have the following forms:

$$-\partial e/\partial x = L \cdot \partial i/\partial t, \quad (13)$$

$$-\partial i/\partial x = K \cdot \partial e/\partial t. \quad (13a)$$

They are essentially the equations of oscillations in a single conductor having a self inductance per unit length L and a capacitance per unit length K, the solutions of which are, as well known, two traveling waves propagating in the opposite directions and can be expressed as follows:

$$i = F(x - vt) + G(x + vt), \quad (14)$$

$$e = Z \cdot F(x - vt) - Z \cdot G(x + vt), \quad (14^1)$$

$$v = 1/\sqrt{LK} = \text{propagation velocity}, \quad (15)$$

$$Z = \sqrt{L/K} = \text{surge impedance}. \quad (16)$$

$F(x - vt)$ is a wave traveling in the positive direction of x, and $G(x + vt)$ in the negative direction of x. The forms of functions F and G can be determined from the boundary conditions.

If we apply the above results to equations (**10**), . . . (**12a**)[1], we get at once the solutions of component currents and voltages:

$$i_2 = F_2(x - v_2 t) + G_2(x + v_2 t), \quad (17)$$

$$e_2 = Z_2[F_2(x - v_2 t) - G_2(x + v_2 t)], \quad (17a)^1$$

$$i_3 = F_3(x - v_3 t) + G_3(x + v_3 t), \quad (18)$$

$$e_3 = Z_3[F_3(x - v_3 t) - G_3(x + v_3 t)], \quad (18a)^1$$

$$\left.\begin{aligned} i_a &= F_a(x - v_1 t) + G_a(x + v_1 t), \\ i_b &= F_b(x - v_1 t) + G_b(x + v_1 t), \\ &\ldots\ldots\ldots\ldots \end{aligned}\right] \quad (19)$$

$$\left.\begin{aligned} e_a &= Z_1[F_a(x - v_1 t) - G_a(x + v_1 t)], \\ e_b &= Z_1[F_b(x - v_1 t) - G_b(x + v_1 t)], \\ &\ldots\ldots\ldots\ldots \end{aligned}\right] \quad (19a)^1$$

in which $Z_1, v_1, Z_2, v_2, Z_3, v_3$ are as expressed by (**1**), (**1a**)[1], (**2**), (**2a**)[1], (**3**) and (**3a**)[1], and

$$\left.\begin{aligned} F_a + F_b + F_c &\equiv 0, & G_a + G_b + G_c &\equiv 0, \\ F_{a1} + F_{b1} + F_{c1} &\equiv 0, & G_{a1} + G_{b1} + G_{c1} &\equiv 0. \end{aligned}\right] \quad (20)$$

By combining the above results according to equations (**6**) and (**8**), we get the general solutions of the oscillation: (omitting $(x - vt)$ and $x + vt)$),

$$\left.\begin{aligned} I_a &= (F_a + G_a) + (F_2 + G_2) + (F_3 + G_3), \\ I_b &= (F_b + G_b) + (F_2 + G_2) + (F_3 + G_3), \\ I_c &= (F_c + G_c) + (F_2 + G_2) + (F_3 + G_3), \end{aligned}\right] \quad (21)$$

$$\left.\begin{aligned} I_{a1} &= (F_{a1} + G_{a1}) + (F_2 + G_2) - (F_3 + G_3), \\ I_{b1} &= (F_{b1} + G_{b1}) + (F_2 + G_2) - (F_3 + G_3), \\ I_{c1} &= (F_{c1} + G_{c1}) + (F_2 + G_2) - (F_3 + G_3), \end{aligned}\right] \quad (22)$$

$$\left.\begin{aligned} E_a &= Z_1(F_a - G_a) + Z_2(F_2 - G_2) + Z_3(F_3 - G_3), \\ E_b &= Z_1(F_b - G_b) + Z_2(F_2 - G_2) + Z_3(F_3 - G_3), \\ E_c &= Z_1(F_c - G_c) + Z_2(F_2 - G_2) + Z_3(F_3 - G_3), \end{aligned}\right] \quad (21a)$$

$$\left.\begin{aligned} E_{a1} &= Z_1(F_{a1} - G_{a1}) + Z_2(F_2 - G_2) - Z_3(F_3 - G_3), \\ E_{b1} &= Z_1(F_{b1} - G_{b1}) + Z_2(F_2 - G_2) - Z_3(F_3 - G_3), \\ E_{c1} &= Z_1(F_{c1} - G_{c1}) + Z_2(F_2 - G_2) - Z_3(F_3 - G_3). \end{aligned}\right] \quad (22a)$$

All F waves travel in the positive direction of x and all G waves in the negative direction of x. By comparing the above equations with the description in the main text, it is seen that the first two terms of the above equations represent the first kind of wave, the second two terms the second kind of wave, and the third two terms the third kind of wave. The equations when the losses are considered can be treated in the same way and resolved into three sub-equations as above.

The forms of functions F's and G's are determined from the initial conditions. Let the distributions of currents and voltages on the six conductors at the instant at which the oscillation begins (when $t = 0$) be $J_a(x), J_b(x), \ldots . J_{c1}(x)$ and $V_a(x), V_b(x), \ldots V_{c1}(x)$. Then we have,

$$J_a(x) = (F_a + G_a) + (F_2 + G_2) + (F_3 + G_3),$$

$$\ldots\ldots\ldots$$

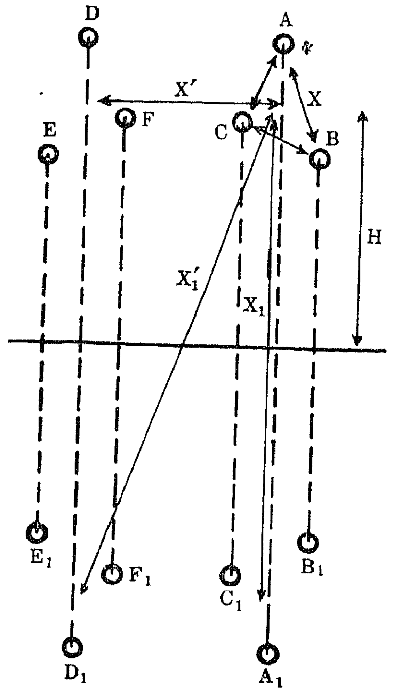

FIG. 6—DIMENSIONS OF LINES

$$V_a(x) = Z_1(F_a - G_a) + Z_2(F_2 - G_2) + Z_3(F_3 - G_3),$$

$$\ldots\ldots\ldots$$

from which

$$F_a = (1/6)(2J_a - J_b - J_c) + (1/6Z_1)(2V_a - V_b - V_c),$$

$$G_a = (1/6)(2J_a - J_b - J_c) - (1/6Z_1)(2V_a - V_b - V_c),$$

and all other functions F and G can be obtained in similar forms. If we put $x - vt$ instead of x in all the F functions and $x + vt$ instead of x in all the G functions and combine them according to (**21**), ... (**22a**), we get the equations of oscillation.

Appendix II

CALCULATION OF LINE CONSTANTS

Assuming that the earth is a perfect conductor, the current in the earth is confined to its surface and the principle of electric image holds. Let the configuration of the lines be as in Fig. 6.

(In Fig. 6,

$H = (1/2) . \sqrt[3]{A A_1 . B B_1 . C C_1}$.

$X = \sqrt[3]{A B . B C . C A}$.

$X_1 = \sqrt[3]{A B_1 . B C_1 . C A_1}$.

$X' = \sqrt[9]{(A F)^2 . (B F)^2 (B D)^2 . A D . B E . C F}$.

$X_1' = \sqrt[9]{(A F_1)^2 . (B F_1)^2 . (B D_1)^2 . A D_1 . B E_1 . C F_1}$.

r = radius of conductor.)

Then we get,

$$L = ((1/2) + 2 . \log . (2H/r)) \times 10^{-9} \quad \text{henry per cm.} \quad (23)$$

$$L_1 = 2 . \log . (X_1/X) \times 10^{-9} \quad \text{henry per cm.} \quad (24)$$

$$L_2 = 2 . \log . (X_1'/X') \times 10^{-9} \quad \text{henry per cm.} \quad (25)$$

Let

P = coefficient of potential per unit length of a conductor,

P_1 = coefficient of potential per unit length between conductors of the same circuit,

P_2 = coefficient of potential per unit length between conductors of the different circuits,

then we have, from the ordinary electrostatics,

$$\left.\begin{array}{l} E_a = P . q_a + P_1 . q_b + P_1 . q_c + P_2(q_{a1} + q_{b1} + q_{c1}), \\ E_b = P_1 . q_a + P . q_b + P_1 . q_c + P_2(q_{a1} + q_{b1} + q_{c1}), \\ \quad . \quad . \quad . \quad . \quad . \quad . \quad . \end{array}\right] \quad (26)$$

where

$$P = 2 . \log . (2H/r) \times 9 \times 10^{11} \quad \text{daraf per cm.} \quad (27)$$

$$P_1 = 2 . \log . (X_1/X) \times 9 \times 10^{11} \quad \text{daraf per cm.} \quad (28)$$

$$P_2 = 2 . \log . (X_1'/X') \times 9 \times 10^{11} \quad \text{daraf per cm.} \quad (29)$$

Equations (**26**) can be rearranged as follows:

$$\left.\begin{array}{l} q_a = K . E_a + K_1 E_b + K_1 E_c \\ \qquad + K_2(E_{a1} + E_{b1} + E_{c1}), \\ q_b = K_1 . E_a + K . E_b + K_1 . E_c \\ \qquad + K_2(E_{a1} + E_{b1} + E_{c1}), \\ \quad . . . . \end{array}\right| \quad (30)$$

see (**5a**) of Appendix I,
in which

$$K = \frac{(P + 2 P_1)(P + P_1) - 6 P_2^2}{(P - P_1)(P + 2 P_1 + 3 P_2)(P + 2 P_1 - 3 P_2)}, \quad (31)$$

$$K_1 = -\frac{(P + 2 P_1) P_1 - 3 P_2^2}{(P - P_1)(P + 2 P_1 + 3 P_2)(P + 2 P_1 - 3 P_2)}, \quad (32)$$

$$K_2 = -\frac{P_2}{(P + 2 P_1 + 3 P_2)(P + 2 P_1 - 3 P_2)}, \quad (33)$$

which are the required coefficients of capacity and induction. It is also seen that,

$$K - K_1 = 1/(P - P_1), \quad . . . . \quad (34)$$

$$K + 2 K_1 + 3 K_2 = 1/(P + 2 P_1 + 3 P_2), . . . \quad (35)$$

$$K + 2 K_1 - 3 K_2 = 1/(P + 2 P_1 - 3 P_2). . . . \quad (36)$$

From these results, the surge impedances and propagation velocities can be calculated. In this case, if we neglect the effect of magnetic flux inside the conductor, (if we drop 1/2 in the expression of L), we get $P/L = P_1/L_1 = P_2/L_2 = 9 \times 10^{20}$, so that $v_1 = v_2 = v_3 = 3 \times 10^{10}$ cm. per sec.

Appendix III

Calculation of Ex. 1.

From the symmetry of the line, we see that the first kind of wave is zero, and all G waves are zero since, at first, only outgoing waves are present. Put E_o = voltage of the source, $E_a = E_b = E_c = E$, $E_{a1} = E_{b1} = E_{c1} = E_1$, $I_a = I_b = I_c = I$, $I_{a1} = I_{b1} = I_{c1} = I_1$, then, $E = Z_2 F_2 + Z_3 F_3$, $E_1 = Z_2 F_2 - Z_3 F_3$, $I = F_2 + F_3$, $I_1 = F_2 - F_3$, (see (**21**), (**22**), (**21a**), (**22a**)) and at $x = 0$, $E = E_o$, $I_1 = 0$, whence, $F_2 = F_3 = E_o/(Z_2 + Z_3)$, and thus the outgoing waves are obtained.

When these waves reach the right end, the reflection occurs. Let G_2 and G_3 be reflected waves. Then

$$E = Z_2 (F_2 - G_2) + Z_3 (F_3 - G_3),$$

$$E_1 = Z_2 (F_2 - G_2) - Z_3 (F_3 - G_3),$$

$$I = (F_3 + G_2) + (F_3 + G_3),$$

$$I_1 = (F_2 + G_2) - (F_3 + G_3),$$

and at the right end

$$E_1 = 0, \ I = 0,$$

from which,

$$G_2 = F_2 (Z_2 - Z_3)/(Z_2 + Z_3) - F_3 . 2 Z_3/(Z_2 + Z_3),$$

$$G_3 = - F_2 . 2 Z_2/(Z_2 + Z_3) - F_3 . (Z_2 - Z_3)/(Z_2 + Z_3).$$

When the G waves reach the left end, they are reflected. The left end of No. 1 acts as a grounded end, hence the reflection is the same as at the right end except No. 1 and No. 2 are interchanged. The oscillation at any instant can be found by superposing all these outgoing and reflected waves.

Discussion

H. G. Brinton: The paper by Mr. Satoh is rather mathematical and has been somewhat difficult to understand. It is based on a previous paper presented in Japan by Dr. Bekku, and perhaps Mr. Satoh assumes that the reader will look up the previous paper and so gives very little explanation himself. The writer has found it possible to understand the paper by first making an analysis from a physical standpoint and then checking Mr. Satoh's equations. As we have no other literature on this phase of the subject it appears desirable to give here a discussion of waves on several parallel wires.

The case to be discussed is that of two parallel three-phase lines. The three wave currents in the three wires of one line are I_a, I_b, and I_c. The three wave currents in the three wires of the other line are $I_a{}^1$, $I_b{}^1$, and $I_c{}^1$. The corresponding potentials of wires to earth are E_a, etc. Thus we have in general six traveling waves of different potential and current on six parallel wires. If we have only one wave on an isolated wire we would calculate the current and energy from the values of voltage and surge impedance, and we would calculate the changes in voltage due to reflection, etc. at points where the circuit constants changed. In the case of several waves on several adjacent wires, the problem is complicated by the magnetic and electrostatic interactions between the various waves. If we have six waves of different potential to consider, then there are six different surge impedances, or ratios of potential to current, to determine; and the surge impedance for each wave is affected by each of the different currents in the five other wires. Thus we have quite a com-

plicated set of interactions and it is necessary to find a method evaluating them.

We shall first explain how it is possible to consider these six currents as the resultants of certain components and thus simplify the problem because of the simpler relations between these theoretical components. Consider first the three wave currents I_a, etc., in the three wires of one three-phase line. If we add these currents, taking account of direction, and then divide by three, we shall have the average value of current in these three wires. The actual current in each wire differs from the average. We shall call these differences I_1, I_2, and I_3. We know that the sum of these differences from the average value must be zero, because otherwise there would be an average difference from an average value which is impossible. Thus we see that the three unequal actual currents are composed of three equal components each having the average value and three unequal components whose sum is zero. In the same way we see that the three unequal currents in the other line are composed of similar components. We can now take the average of the three equal currents of one line plus the three equal currents of the other line. Let this value be called I. This value must be greater than the average value of one line by a certain amount, and less than the average value of the other line by the same amount which we shall call I^1. Then the value of the three equal components in one line is $I + I^1$ and the value of the three equal components in the other line is $I - I^1$. Thus we have reduced the six unequal wave currents in the six wires to the following components. In the three wires of each line there are three unequal components whose sum is zero. In the six wires there are six equal components called I flowing in the same direction. In the three wires of one line there are three equal components called I^1 flowing in one direction; and in the three wires of the other line there are three equal components $-I^1$ flowing in the opposite direction to I^1 in the first line. A further simplification is obtained by considering the three unequal currents of each line whose sum is zero as equivalent to two equal and opposite currents. For example, if we wish to consider the surge impedance Z_1 of the wire in which I_1 is flowing, we can consider the two currents I_2 and I_3 as equivalent to a current $-I_1$ flowing in the opposite direction to I_1.

Then in considering the various components we have only equal currents to consider. When considering equal currents there is only one value of surge impedance to calculate. Thus we have reduced the problem to three sets of components and three surge impedances to be determined.

Before discussing these components further, it is well to state briefly the known relationships in the case of a single wire. In that case, if the wave potential at a given point is known, the wave current is found by dividing the potential by Z_1 the surge impedance. Z is calculated from the formula

$$Z = \sqrt{\frac{L}{C}} \text{ but } v = \frac{1}{\sqrt{L\,C}} = \text{velocity of light}$$

$$\therefore\ Z = \frac{1}{c\,v} \qquad L = \frac{1}{C\,v^2}$$

C is the capacitance to earth of a unit length of the wire and is twice the capacitance from the wire to its image.

If there is another wave of equal voltage and current on a second wire, then the capacitance of the first wire to earth is reduced or increased by the presence of the charge on the second wire, being reduced by a charge of the same sign and increased by a charge of the opposite sign. The capacitance will then be C instead of C per unit length. The inductance of the first wire is also affected by the current in the second wire, but if the waves travel with the velocity of light the product of capacitance and inductance remains constant and it is only necessary to calculate the capacitance as in the simple case of one wire. In the case of two wires the capacitance is then $\alpha\,C$ and the inductance is $\frac{1}{\alpha\,C\,v^2}$ and the surge impedance is

$$Z_1 = \frac{1}{\alpha\,C\,v}$$

This is the formula for surge impedance in the case of the component current I_1 and its opposite $-I_1$ in the first line, and also in the case of I_1^1 and $-I_1^1$ in the second line. If we assume, as Mr. Satoh does, that the two equal but opposite currents of one line would have zero resultant affect on the other line, then this formula for Z_1 holds true when these particular current components are flowing in the two lines at the same time. The voltage components corresponding to these current components are

$$\begin{array}{ll} E_1 = I_1\,Z_1 & E_1^1 = I_1^1\,Z_1 \\ E_2 = I_2\,Z_1 & E_2^1 = I_2^1\,Z_1 \\ E_3 = I_3\,Z_1 & E_3^1 = I_3^1\,Z_1^1 \end{array}$$

There is only one value of surge impedance for these components because the three wires of each line are assumed to be under the same influences. These assumptions do not correspond exactly to any conditions existing in practise, but they are satisfactory for the purpose of aiding us to obtain a fair general conception of the wave relationships.

We may next consider the current and voltage components in the case of the six equal components in the same direction in the six wires. In this case the capacitance of each wire to earth is reduced. If we assume, as Mr. Satoh does, that each wave is equally affected by the other five, then the capacitance of each wire is reduced by the same factor which we may designate as B. Then in the same way as above we see that the surge impedance of each wire is

$$Z_2 = \frac{1}{B\,C\,v}$$

We then have for each wire $\qquad E = Z_2\,I$

The third set of components to be considered are those consisting of three equal currents I^1 in one direction in the three wires of one circuit and three equal currents $-I^1$ in the opposite direction in the other circuit. In this case the capacitance to earth of one wire is $\gamma\,C$ instead of C. Assuming each of the six wires is under the same influences, this value C applies to each wire. The corresponding value of surge impedance is

$$Z^1 = \frac{1}{\gamma\,C\,v}$$

In the above we have started with six waves of given current. In the same way we can start with six waves of given voltage and then calculate the wave currents after determining the surge impedances. For example, we would first find the average value E for the six waves. The average value for one circuit would be $E + E^1$ and for the other circuit $E - E^1$. The differences E_1 and E_1^1 could then be determined, knowing the total voltages E_a and E_a^1. After determining the various surge impedances $Z_1\,Z$ and Z^1, the current components could be calculated and the total current in any wire would then be the sum of the components in that wire.

In order to determine the various surge impedances, it is necessary to calculate C and the factors α, β, and γ which depend upon the amount that the capacitances are affected by the presence of the other charges. There are several ways of doing this. One way is to work with unit quantities and determine how much the potential at one wire is affected by the presence of the charges on the other wires. For example, in the case of Z_1 we have to consider two wires oppositely charged. The effect of the unit charge of one wire is to make it have the potential,

$$4.6 \log \frac{2\,h}{r}$$

where h is the elevation of the wire and r is its radius. The opposite charge on the second wire decreases the potential of the first wire by the amount,

$$4.6 \log \frac{r_2}{r_1}$$

where r_1 is the distance to the second wire and r_2 is the distance to its image. Therefore the potential of the first wire is decreased by the factor

$$\frac{\log \frac{2\,h}{r} - \log \frac{r_2}{r_1}}{\log \frac{2\,h}{r}}$$

Since in the case of unit given charge the voltage is inversely proportional to the capacity we can say that the capacity of the wire is increased by the factor

$$\alpha = \frac{\log \frac{2\,h}{r}}{\log \frac{2\,h}{r} - \log \frac{r_2}{r_1}}$$

The factor B is determined in the same way, remembering that the charges are all of the same sign in this case and that there are six charges to be considered. Mr. Satoh uses an average value for the distance of the three wires of one circuit to one wire of the other circuit. Calling this distance $r_1{}^1$ and the distance to its image $r_2{}^1$ we see that the factor is

$$\beta = \frac{\log \frac{2\,h}{r}}{\log \frac{2\,h}{r} + 2 \log \frac{r_2}{r_1} + 3 \log \frac{r_2{}^1}{r_1{}^1}}$$

The factor γ is calculated in the same way. Remembering that in this case the three charges of one circuit are opposite in sign to those of the other circuit, we see that

$$\gamma = \frac{\log \frac{2\,h}{r}}{\log \frac{2\,h}{r} + 2 \log \frac{r_2}{r_1} - 3 \log \frac{r_2{}^1}{r_1{}^1}}$$

Mr. Satoh does not use the above factors because he adds to or subtracts something from C to take account of the effect of the other charges instead of multiplying C by a factor. We have used the factor method for the sake of simplicity.

Mr. Satoh gives some interesting diagrams showing rectangular waves on parallel wires and the effect of certain changes in circuit constants. He gives the calculations for the case of three equal waves on three wires of one circuit due to an impressed d-c. voltage and three equal but smaller voltage waves on three wires of a parallel circuit due to induction from the first circuit. However, he apparently omits the calculation of the values of the induced wave which are the really important unknowns; and in the diagram the induced charges in the second circuit are incorrectly shown as having the same sign as the charges in the first circuit. These specific cases will require some further study and it therefore seems best to consider them separately. One point of interest to us is the fact that when waves of about equal voltage arrive at a station on the three wires of a circuit, which perhaps is the usual occurrence, the surge impedance is greater by a considerable percentage than in the case of a single wire, and so the wave-current and energy is correspondingly less.

R. J. C. Wood: Some time ago we made some tests on 220-kv. lines of the Southern California Edison Company in order to get some idea of the frequency and magnitude of the surges that were actually occurring on the line. To help in this work the Westinghouse Company installed a number of klydonographs, and I wrote a paper about the results.

One of the main points brought out which had a bearing on the actual transmission line was that surges are quite rapidly damped in traveling along the lines.

Looking at the pictures of the waves shown in the paper one is led to think the wave is going to double up at the points of reflection, and amount to something which may be quite serious; but actually, on the line, these waves attenuate very fast. In fact we got measurements of surges about 100 or 150 per cent above normal at one station and 35 mi. away there was no indication on the instrument of there being any surge at all; this does not mean that there was no surge at all but that it had been reduced to not more than some 25 or 50 per cent above normal.

E. R. Stauffacher: There has been a number of cases on two 66-kv. lines single-tower, double-line construction, where the evidence of trouble on one of the lines has been found; but every indication regarding the relay operation pointed to the possibility of a trouble on the adjacent line.

I wonder if Mr. Terman would give us a little light as to what might have happened on the second line due to a wave of high voltage induced on the second line, when the trouble originated on the first line.

It would be one way of explaining some rather peculiar and erratic relay operations. Otherwise we have to accept the theory that the trouble was not cleared promptly enough on the first line in trouble and the arc went over into the other circuit.

D. I. Cone: This paper presents in clear perspective and in generalized form the propagation of waves in a double-circuit line. An illustration of the practical utilization of the three paths described occurs in the four-conductor arrangement common in communication practise comprising (1) two side circuits, one on each pair of wires; (2) "an earth return circuit using the four wires in parallel as one side," (The second path is very important from the standpoint of induction from external sources. It may also be used for communication purposes as in the simplex phantom telegraph circuit); and (3) a phantom "using each of these paths as one of its sides."

The impedances of the three paths for steady-state conditions at voice and higher frequencies are of the order of 700 ohms, 400 ohms, and 300 ohms respectively for circuits of the ordinary open-wire construction. These figures are closely similar to the surge-impedance figures for typical power circuits given in the paper.

The assumption is stated that the earth's surface is considered as a surface of infinite conductivity, giving a speed of propagation equal to that of light. In practise, for earth-return circuits the apparent speed of propagation, calculated from steady-state measurements may be less, by 20 per cent or more, due to such effects as the increased inductance per unit length of the circuit by reason of its penetration into the earth.

Mr. Satoh's seventh conclusion states: "Inductive interference to neighboring telephone circuits from the transmission lines is caused only by the second kind of wave and can be easily calculated," meaning the case of the several wires with earth return. He assumes throughout the situation in which the influence of each of the three conductors of any one of the circuits on its neighbors is the same; that is, that each circuit is so thoroughly transposed or the wires are so disposed with reference to this circuit that the influence of each of the three wires is the same on any outside circuit; and with that limitation the statement as made is correct. In the ordinary case that is not strictly true.

In the work of inductive coordination, the separations being secured in present practise are such, that often the only problem is that of the second kind of wave. These give an influence which spreads out to great separations.

Joseph Slepian: The work of Mr. Satoh is an interesting application of the resolution of a system of voltages and currents which are tied together by linear relations, into sets of normal components; that is into sets in each of which each voltage is proportional to its corresponding current.

The best example we have had before the Institute of the

resolution of a system in this way was in the paper by Mr. C. L. Fortescue on Symmetrical Coordinates of nine years ago. In dealing with three-phase systems Mr. Fortescue resolved the line voltages and currents, $(E_a, E_b, E_c, I_a, I_b, I_c)$ into three sets of symmetrical components $(E_0, E_0\, E_0, I_0\, I_0, I_0)$, $(E_1, a^2 E_1, a E_1, I_1, a^2 I_1, a I_1)$, and $(E_2, a E_2, a^2 E_2, I_2, a I_2, a^2 I_2)$, where a is a complex cube root of unity. Evidently in each of Mr. Fortescue's symmetrical components, each voltage is proportional to its corresponding current, and in addition to this simplicity to begin with, the equations for a symmetrical rotating machine take on the extremely simple form, $E_0 = Z_0 I_0$, $E_1 = Z_1 I_1$, $E_2 = Z_2 I_2$.

It is interesting to examine the general equations for the propagation of waves on parallel wires from this point of view and obtain the normal component waves of Bekku and Satoh. Neglecting resistances and leakages, and confining ourselves to the case of three wires, we have in general, if E_a, E_b, E_c are the line voltages, and I_a, I_b, I_c the corresponding line currents in a traveling wave, the three equations

$$\begin{aligned} E_a &= Z_{aa} I_a + Z_{ab} I_b + Z_{ac} I_c \\ E_b &= Z_{ba} I_a + Z_{bb} I_b + Z_{bc} I_c \\ E_c &= Z_{ca} I_a + Z_{cb} I_b + Z_{cc} I_c \end{aligned} \qquad (1)$$

We then put the problem of finding a wave such that in it the corresponding voltages and currents are proportional, *i. e.*, such that $E_a = Z I_a$, $E_b = Z I_b$, $E_c = Z I_c$.

Substituting in the wave equations we get

$$\begin{aligned} 0 &= (Z_{aa} - Z) I_a + Z_{ab} I_b + Z_{ac} I_c \\ 0 &= Z_{ba} I_a + (Z_{bb} - Z) I_b + Z_{bc} I_c \\ 0 &= Z_{ca} I_a + Z_{cb} I_b + (Z_{cc} - Z) I_c \end{aligned} \qquad (2)$$

In general this set of equations has only one solution namely $I_a = I_b = I_c = 0$. It will have other solutions, if and only if the determinant of the coefficients vanishes, that is, if

$$\begin{vmatrix} Z_{aa} - Z & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} - Z & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} - Z \end{vmatrix} = 0 \qquad (3)$$

This is a cubic equation for Z, and in general, has three roots Z_1, Z_2, Z_3. There are then generally three normal component waves, each with its own surge impedance, Z_1, Z_2, or Z_3. The relation between the line currents or voltages in any one component wave is given by substituting the appropriate value of Z in (2) and solving for the ratios between I_a, I_b, and I_c. Any arbitrary wave can be resolved into the sum of three normal component waves, and in terms of these normal components the wave equations (1) become

$$E_1 = Z_1 I_1 \qquad E_2 = Z_2 I_2 \text{ and } E_3 = Z_3 I_3 \qquad (4)$$

When the three lines are completely transposed, as in the case considered by Bekku, we have $Z_{aa} = Z_{bb} = Z_{cc}$, and $Z_{ab} = Z_{ba} = Z_{bc} = Z_{cb} = Z_{ca} = Z_{ac} = 0$, and equation (3) reduces to

$$(Z_{aa} - Z_{ab} - Z)^2 (Z_{aa} + 2 Z_{ab} - Z) = 0 \qquad (5)$$

This is a degenerate case in which two of the roots are equal, $Z_1 = Z_2 = Z_{aa} - Z_{ab}$, and the third root $Z_3 = Z_{aa} + 2 Z_{ab}$. Two of the normal component waves become indistinguishable then. Applying equations (2) we find that for the first two normal component waves, (indistinguishable from each other) $I_a + I_b + I_c = 0$, and for the third wave, $I_a = I_b = I_c$. In any wave then in which $I_a + I_b + I_c = 0$, we will have $E_a = Z_1 I_a$, $E_b = Z_1 I_b$, $E_c = Z_1 I_c$, and in any wave in which $I_a = I_b = I_c$, we will have $E_a = Z_3 I_a$, $E_b = Z_3 I_b$, $E_c = Z_3 I_c$. Any arbitrary wave can be resolved into a superposition of two waves of these types.

The general case of six wires can be treated as above, leading to six normal component waves. Where the six wires consist of two sets of three, each completely transposed, the six component waves will degenerate into the three of Satoh.

F. E. Terman: I wish to begin by making some comments on the paper for myself. The value of Mr. Satoh's paper is that it gives a method whereby we can determine the magnitudes and effects of waves as they actually exist on the transmission line. The classical case of a wave between two conductors, given in our textbooks, fails in many instances to cover the practical situation.

By introducing slight modifications, Mr. Satoh's method of attack can be applied to cases other than the thoroughly transposed double-circuit three-phase line. For example, I think there would be no difficulty in solving the case of a three-phase line paralleled by a two-wire telephone line, and it seems that the same mode of attack might be of assistance in finding out something about the effect of a ground wire on waves. The ground wire is grounded at frequent intervals, which complicates the problem, but a solution for a simplified ideal case looks possible.

Since the author of this paper is now in Germany, I have the somewhat difficult task of taking the author's place in answering points that have been brought up.

In the supplementary discussion, Mr. Brinton gives a very good physical picture of the mathematical solution given in the paper. I do not agree with him on several points raised in the last paragraph of his discussion, however. The paper does include the induced transients. The equations for determining the magnitude of the induced transient are given in the example, and the induced waves are clearly shown in the figures, such as Circuit No. 2, Fig. 3. The signs of the waves as given by Mr. Satoh are also correct. These waves represent voltage, not charge, and it is even possible to raise a wire above ground potential without any net charge on it if the wire is in a suitable electrostatic field.

I remember Mr. Wood's article giving data on the attenuation of waves, and the unexpectedly high attenuation found for actual transmission lines undoubtedly does much to minimize the dangerous effects of lightning and other disturbances at some distances from the trouble. Near the origin of the trouble the effects are still severe for at such points the waves have not attenuated appreciably. The effect of the high attenuation is to localize the region of danger, but does not in any way influence the severity of the disturbance near the source of trouble, by doubling of voltage waves, etc.

Troubles such as described by Mr. Stauffacher might certainly be caused by induced waves, although a study of individual cases would be necessary to determine whether this was the real factor rather than other possible causes, when considering a specific type of trouble. The example given in Fig. 3 of the paper shows how trouble on one circuit will induce voltages on a second circuit, and if this induced wave reaches a transformer its voltage will double and might flash over a weak place.

Mr. Cone's remarks are interesting and to the point. It might be added that the reflection of the steady-state wave caused by the resistance of the transmission system is one of the reasons why the velocity of phase propagation in the steady state is not as great as the velocity of light.

The remarks of Dr. Slepian need no comment. They are complete in themselves, and I greatly enjoyed reading his clear statement of the general principles involved.

In conclusion I wish to state that this paper was written from material incorporated in a thesis Satoh wrote at Stanford, and the paper is very condensed compared with the thesis, which contains much more material than is presented here. For example, Satoh worked out 15 to 20 numerical examples, and the theory has been worked out better than space permits him to show in this paper. He has also worked out the solution of the double-circuit line under steady-state conditions, taking into account mutual inductive and electrostatic effects, and applied Fortescue's symmetrical-coordinate system to solve cases of unbalance. Another section of the thesis worked out the differential equations of the six-wire line not neglecting losses. His results give three waves, each attenuated by the losses independently of the presence or absence of other waves. The actual solution of these equations including losses was not made, but can be found in the literature of mathematical physics.

The thesis upon which this paper is based and which covers these additional parts, is in the Stanford Library, and is available to anyone who would find it useful.

Transients Due to Short Circuits

A Study of Tests Made on the Southern California Edison 220-Kv. System

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Synopsis.—*The paper deals with records which have been obtained during short circuits upon the Southern California Edison's 220-kv. system. The main features of the system are outlined, and such operating data as are necessary to afford an understanding of the various conditions which have to be met are included. The general scheme of relays is described, and the causes of flashovers and their times of occurrence are tabulated, together with the percentages which cause interruptions to service. Whether or not interruption is caused is found to depend, among other things, upon the load being carried at the time. With load below 150,000 kw., there are no interruptions unless relays are inoperative. A number of typical records of short circuits are shown and analyzed. It is shown that large amounts of power are consumed in short circuits, but that this is dependent upon the ground resistance. Practically all short circuits are single-phase to ground. The advantage of low-reactance machines is discussed and the various factors that prevent loss of synchronism pointed out. The records show that there is but little if any tendency for synchronous machines at either end of the line to fall out of step among themselves as a group, but that the sending end under certain conditions will get out of step with the receiving end.*

Introduction

The ever increasing necessity of transmitting greater power over longer distances at higher voltages has led to considerable study during the last few years of the factors affecting the power limits of transmission systems. The ability of such a system to withstand short circuits without experiencing more than momentary disturbance is of the greatest importance in determining its economic capacity rating. The problem was first attacked by theoretical analysis, concentrating upon the steady state or static limits. Supplementary shop tests were made, in so far as a power system could be duplicated in miniature, but assurance was still lacking that the results obtained would apply to actual systems.

Subsequent analysis and observation of power systems indicated that their behavior during transients, such as those caused by short circuits and switching, was of the greatest importance. A very large amount of theoretical work was done in connection with this phase of the problem and an extensive series of tests was made upon the Pit River system of the Pacific Gas and Electric Co. The results of this work are described in two papers before the institute.[3] The close agreement between the results of the test and calculations indicated that any specific condition on a given system can be analyzed mathematically with a reasonable degree of accuracy, and the system designed accordingly. However, to obtain the over-all performance of a system, it is necessary to know not only its performance under stated conditions but also the character and frequency with which such conditions will be met in practise.

The Southern California Edison Company's Big Creek lines have been operated at 220 kv. since May 6, 1923. Prior to that time, no automatic relaying of sections of the line was in use. Since relays have been in operation, the larger percentage of faults have been cleared without interruption to service; some of the short circuits occurring at times of heavy load have caused the two ends of the system to go out of step even after proper elimination of a faulty section of line by relays. This has happened also as a result of heavy short circuits on 60-kv. lines out of 220-kv. substations.

In order to obtain information as to just what happened on this system under these abnormal conditions, special recording instruments were furnished by the Westinghouse Company and installed at a number of points upon the system. By their use, data as to the type of trouble and its effect upon the system have been recorded.

The purpose of this paper is to present the results of this investigation, which has been going on since August, 1925. Although the details of the disturbances encountered will undoubtedly be different on other systems in different localities, yet there will be points in common, and the range of conditions to be met will probably be of at least the same order on all systems, and the analysis be of more than local application.

Description of the System

The detailed description of the Big Creek System has been published many times and only the main items will be included in this paper.

The general design of the generating plants follows the unit system; that is, generator and transformer are connected as a unit to the higher-tension bus.

The single-line diagram of the Big Creek system,

1. Southern California Edison Company, Los Angeles, Calif.
2. Westinghouse Electric & Mfg. Company, E. Pittsburgh, Pa.
3. *Studies of Transmission Stability*, by R. D. Evans and C. F. Wagner. *Practical Aspects of System Stability*, by Roy Wilkins, A. I. E. E. TRANS., Vol. 45, p. 41.

Presented at the Pacific Coast Convention of the A. I. E. E., Del Monte, Calif., Sept. 13-16, 1927.

Fig. 1, shows the unit system (220-kv.) at each station. A description of each machine at the 220-kv. stations is given in Table I.

The old Big Creek tower lines spaced 82 ft., center to center carry 605,000 cir. mil, aluminum conductors steel reinforced, spaced 17.25 ft., horizontally from Big

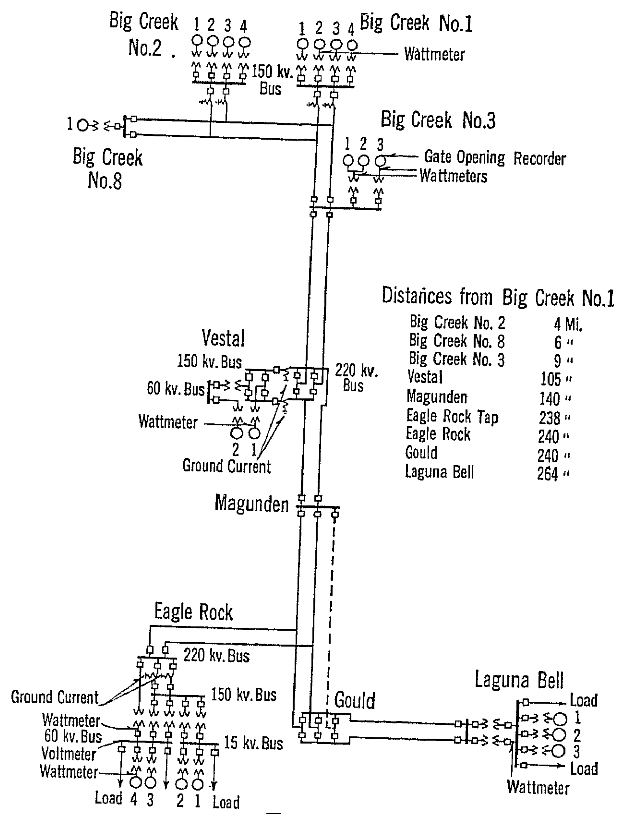

FIG. 1

Creek No. 1 to Eagle Rock. The Laguna Bell tap is of similar construction with 666,600-cir. mil, aluminum conductors steel reinforced, spaced 22.25 ft. with tower lines on 156-ft. centers. The new Vincent line with 1,033,500-cir. mil, aluminum conductors steel reinforced, spaced 22.25 ft. follows an entirely different right-of-way, averaging approximately 18 mi. east of the two lines.

The Vestal substation was built primarily for the purpose of supplying power to the 60-cycle systems in the San Joaquin Valley, with an occasional interchange of power. It also serves as a switching and sectionalizing station for the 220-kv. lines.

Magunden and Gould are switching and sectionalizing stations only. Eagle Rock and Laguna Bell are the two main terminal stations from which the greater part of the power is distributed to the 60-kv. network.

At present, power from the Long Beach Steam Plant (total capacity of 200,000 kv-a.) is normally absorbed in the 60-kv. system; under certain conditions of load and during flashovers on the 220-kv. lines, steam power may be transmitted over 60-kv. lines through either or both Eagle Rock and Laguna Bell stations, the greater amount going through Laguna Bell on account of a more direct connection.

Kern River No. 3 (capacity 35,000 kv-a.) transmits power to Vestal over two 60-kv. lines. Other small plants are connected to the 60-kv. system at different points.

220-Kv. Relay System

Since the 220-kv. transmission system of the Southern California Edison Company is the backbone of the entire system, the importance of perfect automatic sectionalizing is supreme. Statistics show that approximately all failures on the 220-kv. lines are one phase to ground. Therefore the most important protection on these lines is the ground fault protection. Since faults must be cleared in a very short time to prevent interruption, a scheme that is not extremely fast in operation should not be used.

The study of protection against phase-to-phase faults is made by means of the ordinary calculating board; this alone is not sufficient, as protection is required against single-line faults to ground. The application of relays to satisfy this latter requirement requires the study of zero sequence, or residual currents.

For instance, due to the fact that the two Big Creek lines are relatively close together as compared to space separating them from the Vincent line and the return ground paths, the phase-to-ground reactance of the two Big Creek lines in parallel is only slightly less than the single Vincent line. Therefore, the Vincent line will have more ground fault current than either the Big Creek lines with ground faults north of Magunden or south of Gould. However, with one Big Creek line out, the other Big Creek line will balance up with the Vincent line.

Many relay schemes were devised and tried out on actual dummy systems. The one that proved most successful was the current balanced relays for phase-to-phase and phase-to-ground faults. All the Big Creek plants—Vestal, Magunden north, Eagle Rock, Gould south, and Laguna Bell - are equipped with two-line phase and ground balance current relays as shown schemati-

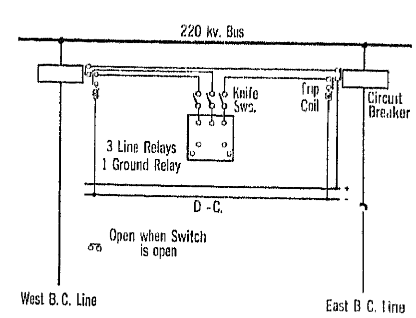

FIG. 2

cally in Fig. 2. These are so connected that the tripping circuit is opened by auxiliary switches when either line oil switches are opened, thus leaving the second line in any one section non-automatic. Magunden, south, and Gould, north, are equipped with three-line phase and ground balanced relays. These are so connected that

TABLE I
220-KV. STATION APPARATUS

	Synchronous machine			Transformer			
Plant	Unit	Size in kv-a.	% leakage reactance	Size in kv-a.	% leakage reactance	Ratio	Connection
Big Creek No. 1..........	Generator No. 1	17,500	22	17,500	8.2	6.6/150	Δ/Y
	" No. 2	17,500	22	17,500	8.2	6.6/150	Δ/Y
	" No. 3	17,500	22	17,500	8.2	6.6/150	Δ/Y
	" No. 4	28,000	24.5	28,000	8.5	11/150	Δ/Y
				52,500	9.6	150/220	Y/Y
				52,500	9.6	150/220	Y/Y
Big Creek No. 2..........	Generator No. 1	17,500	24	17,500	8.5	6.6/150	Δ/Y
	" No. 2	17,500	24	17,500	8.5	6.6/150	Δ/Y
	" No. 3	17,500	24	17,500	8.5	6.6/150	Δ/Y
	" No. 4	17,500	24	17,500	8.5	6.6/150	Δ/Y
				52,500	9.6	150/220	Y/Y
				52,500	9.6	150/220	Y/Y
Big Creek No. 3..........	Generator No. 1	28,000	20.8 }	55,500	7.7	11/220	Δ/Y
	" No. 2	28,000	20.8 }				
	" No. 3	28,000	20.8	55,500	7.7	11/220	Δ/Y
Big Creek No. 8..........	Generator No. 1	25,000	12.7	60,000	12.3	11/220	Δ/Y
Vestal..................	Frequency changer No. 1	15,000	22	13,500	8.7	150/15	Δ/Δ
	Frequency changer No. 2	15,000	23	15,000	9.3	69/12	Y/Δ
				52,500	9.6	220/150	Y/Y
				52,500	9.6	220/150	Y/Y
				34,500	9	150/66	Δ/Y
Eagle Rock..............	Condenser No. 1	15,000	20.5	15,000	8.3	18/6.6	Δ/Δ
	" No. 2	15,000	17.5	15,000	8.3	18/6.6	Δ/Δ
	" No. 3	30,000	18.2	30,000	9	69.6/6.6	Y/Δ
	" No. 4	30,000	22.5	35,000	10.8	69/6.6	Y/Δ
				110,000	9.3	220/150	Y/Y
				110,000	9.3	220/150	Y/Y
				75,000	12.7	220/66	Y/Δ
				34,500	8.7	150/66	Δ/Y
				34,500	8.7	150/66	Δ/Y
				13,500	8.2	135/15	Δ/Δ
				13,500	8.7	135/15	Δ/Δ
Laguna Bell............	Condenser No. 1	30,000	13	30,000	9	69/6.6	Y/Δ
	" No. 2	30,000	22.5	35,000	10.9	69/6.6	Y/Δ
	" No. 3	30,000	22.5	35,000	10.9	69/6.6	Y/Δ
				60,000	18	220/69	Y/Δ
				60,000	18	220/69.	Y/Δ

All transformers star-connected have neutrals solidly grounded.

if any one-line oil switches are opened the tripping circuits of the two sets of relays involved are opened, leaving balance protection between the remaining two lines in similar manner as above. Thus with two line switches opened the remaining line is non-automatic.

Since Eagle Rock is tapped off the two Big Creek lines near Gould, the perfect three-line balance between

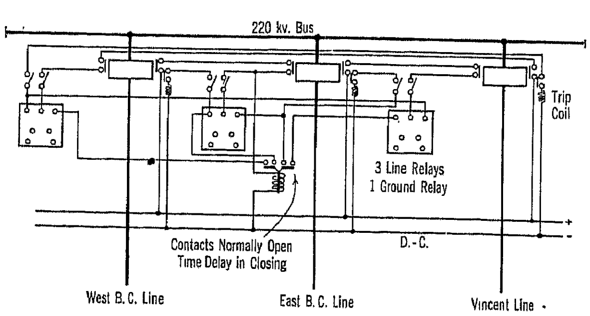

Fig. 3

Magunden and Gould is destroyed. In order to keep the balance relays from functioning improperly an auxiliary relay is used that will open the tripping circuit of the two Big Creek lines from the relays that balance the two Big Creek lines with the Vincent line, allowing only the balanced relays between the two Big Creek lines for clearing trouble on either line. There is shown schematically the three-line balance current relays in Fig. 3. In case one Big Creek line is tripped out, this auxiliary relay, after a delay of from three to five seconds, closes the tripping circuit to the other Big Creek line, through the relay that is balanced with the Vincent line. With a fault just out of Gould on one Big Creek line, the first switch to open is that line switch at Gould. The instant after this switch has opened, the current in the other Big Creek line at Gould is much greater than the current in the Vincent line. But since the tripping circuit of Big Creek line side of this relay is interrupted, the good Big Creek line cannot be tripped. However, immediately the proper switches at Eagle Rock and Magunden open clearing the trouble. In a few seconds later the tripping circuit of the remaining Big Creek line is completed by the time delay auxiliary relay.

Flashover Suppressors

In the case of trouble on the last or single line in any section, ordinarily the arc can be broken only by lowering the voltage of the system. This is done by actuating a time relay by means of ground current at all the Big Creek generating and 220-kv. substations,

which, in some cases, trips the voltage regulator, and in others, starts a motor-driven rheostat to lower the exciter voltage of the generators and condensers. The motor-driven rheostats proved too slow and complicated and had a variable time of operation. This has been changed to a contactor which normally short-circuits an adjustable resistance in the exciter field and which is opened in cases of continued excessive ground current. As soon as the ground current ceases to flow, the contactor is closed, cutting out this resistor and allowing the exciters to pick up. The resistance must be properly adjusted; if too small, sufficient voltage drop is not obtained, whereas, too high a resistance may permit the exciter polarity to reverse.

Distribution of Loads

The division of power generated at Big Creek and Long Beach steam plants varies greatly throughout the year and is dependent upon the season and the load demand. During the spring run-off at Big Creek plants, these plants supply the greater part of the load, the steam being used for supplying peak demands only. During this time and early summer the main reservoir,

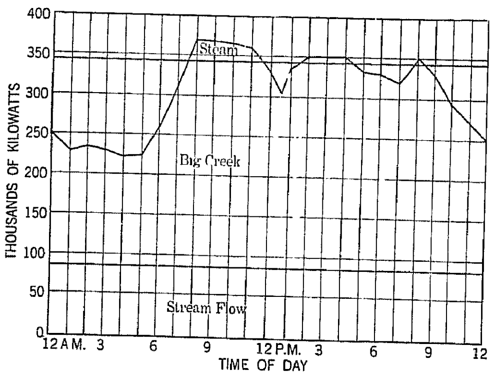

Fig. 4

(Huntington Lake reservoir with a capacity of 88,000 acre-ft.) is filled.

The heaviest loads occur during the months of June, July, and August. Thus, after the run-off period and the lake has been filled, steam and stream flow plants run on block loads, and Big Creek plants use stored water for making up peak loads. The stored water has to supply peak power up to the time of next run-off; therefore, the rate at which the stored water is used is somewhat fixed, accounting for a definite amount of power; the remainder of the demand is supplied by steam.

The period of spring run-off is illustrated by Fig. 4—the daily load chart for June 8, 1926. The maximum hydraulic output possible was the maximum rating of the machines at this time, or 345,000 kw. None of the stream-flow plants has storage; their output is equivalent to the actual stream flow at any time. Since the load exceeded the total hydro generation, it was necessary to supply the peak loads with steam as indicated. It will be noticed that the maximum demand at Big Creek was 257,000 kw. and the minimum was 132,000 kw., the low load being from 12:00 midnight to 6:00 a. m.

The period after the run-off is shown by Fig. 5, the daily load chart of July 27, 1926. The steam plant supplied a constant load of 110,000 kw., while the remaining portion of the load ranging from 50,000 kw. to 210,000 kw. was supplied by the Big Creek plants,

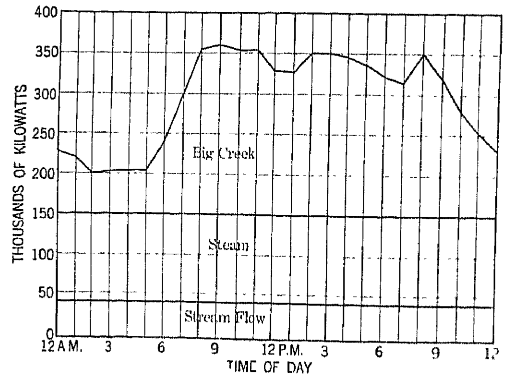

Fig. 5

the low load again being between 12:00 midnight and 6:00 a. m.

Fig. 6 is a yearly kw-hr. output chart showing the distribution of energy between the Big Creek plants and the Long Beach Steam Plant. It can be seen that during the months of April, May, and June a very small amount of steam power is generated. The transformer capacity at the various substations on the Big Creek lines is shown by Table I.

Power Dispatching and Governing

The production engineer, having charts and measurements of the behavior of the whole system calculates from this information the amount of load to be carried at the various plants. Accordingly, the men in charge of the plants are informed as to the amount of power

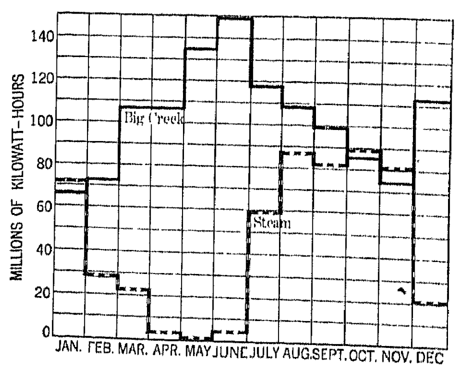

Fig. 6

to be generated. The general method of operation is to have one plant do the regulating while the others carry block loads.

Operation of Relays

The normal operation on the 220-kv. lines is to have the balanced relays in service. When a fault occurs near one station it generally clears at that station first due to the greater unbalance. Since the relay trip

circuits are interlocked to be automatic only when both line switches are closed, the relays, after one line has opened, automatically become non-automatic. In order to have protection upon the faulty line when testing, it is necessary to arrange the balanced current relay to trip on that line only. Therefore, knife switches are properly connected for the purpose. In case the line trouble has been removed, the switch will remain closed,

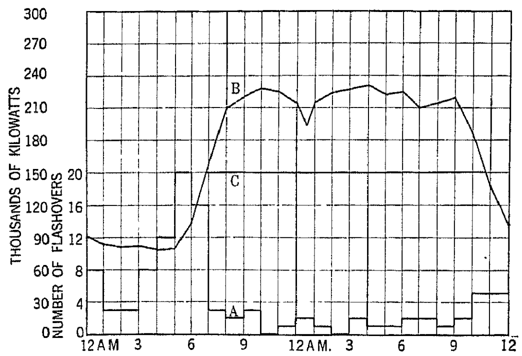

FIG. 7

and in order to re-establish load over this line, the balance current relays are then made non-automatic at each end of the section, the oil switch being closed in at the other end of the line. The relays are then made automatic.

When all the 220-kv. lines are automatic the flashover suppressors are left out of service. But when a section of one line is out for repair, or otherwise, and the remaining line in this section is non-automatic, the flashover suppressors are placed in service. In case a flashover occurs on this one section of line, the flashover suppressors will operate. If, however, the fault should occur on a section of lines where relay protection is in service the relays will clear the fault before the flashover suppressors are brought into action, due to the fact that the suppressors have a minimum definite time of operation sufficient to allow clearance of line by line relays.

The current setting of the line balance relays is sufficiently high to allow maximum load current to flow on one line with zero current in the other without causing the relays to operate. This is done so that if, by accident, one line switch be opened in one section, the relays will not open the good line switch at the other end of the same section. The ground balance current relay setting is not affected by load conditions. Therefore, in a straight, two-line section, the ground balance relays may be set as sensitively as desired. In the section between Magunden and Gould, however, the ground relays balancing the Big Creek lines with the Vincent line must be set so high that the unbalanced ground current due to the difference of ground impedance of the three lines, with a through, short-circuit, is insufficient to operate the relays.

Time and Causes of Flashovers

The total number of flashovers on the 220-kv. lines from January 1, 1924 to May 1, 1927, occurring during the various hours of the day is shown by Curve *A*, Fig. 7. Curve *B* is an average daily load curve for one year. It will be seen that most of the flashovers have occurred between the hours of 3 a. m. to 7 a. m., during the light load period. Line *C*, indicating the load below which flashover does not cause outage shows correct relay operation and will be discussed later. (Refer also to Fig. 8.)

TABLE II
CAUSES OF FLASHOVERS

Bird trouble	82*	phase to ground
Bushing flashover	3	"
Fire under line	2	"
Hay derrick in line	2	"
Wire of Ford spark coil thrown in line	1	"
Vine in line	1	"
Bus flashover	1	"
Cable splice broke	1	"
Disconnect fell open	1	"
Unknown	2	"

*One of these flashovers, due to strong wind, blew from phase to ground to phase to phase to ground.

Table II shows the causes of flashovers, also the kind of flashover; phase-to-phase, or phase-to-ground.

Table III shows the data of flashovers on 220-kv. lines occurring during the period of tests.

Restoration of Service

Ordinarily when a section of line is cleared by relays, the service is not interrupted. Some times, with heavy loads, however, the shock to the system is too great and the Big Creek end and the receiving end fall out of step with each other. In this case, the steam plant picks up as much load as possible and the Big Creek plants try to hold normal speed. In the meantime, sufficient load is dropped, accidently or otherwise, so that the plants can pull up the load to normal speed. Normally this may take from one minute up to several.

When a flashover occurs on a non-automatic section of line, the flashover suppressors lower the voltage and as soon as the arc breaks bring the voltage up. The devices are timed to make this complete operation in 15 sec. Sometimes, at heavily loaded periods, the driving force at Big Creek pulls out of step with the rest of the system by over speeding. The system is

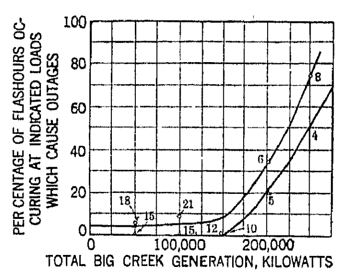

FIG. 8

brought back together in a similar way as above but usually takes a little longer.

System Outage

The proportion of times the system is likely to be put out of service due to flashovers is variable, depending upon the load, system connections, and the severity of the trouble.

Fig. 8 is a chart showing what the percentage of

TABLE III

Date	Connected kv-a.	Big Creek generation	Total ground amperes	Location of fault	Relay operation	System operation
			1925			
8–23	245,000	31,000	1080	127	⊙	
8–26	265,500	64,000	1050	Eagle Bell	△	
8–27	280,500	53,000	850	Laguna Bell	⊙	
9–3	424,500	201,000	1140	Bus B. C. No. 1	△	
9–8	340,500	131,000	980	141	△	
9–13	248,000	21,000	1080	102	⊙	
9–21	197,500	25,000	580	59	⊙	
10–2	381,000	146,000	610	136	⊙	
10–3	248,000	60,000	1060	142	⊠	
10–18	239,000	72,000	1110	126	⊙	
10–19	160,000	0	770	95	⊙	
10–21	207,500	26,000	800	103	⊙	
10–25	361,500	97,000	230	. .	⊙	
10–25	359,500	144,000	1030	77	⊙	
10–26	245,500	72,000	1150	95	⊙	
10–30	275,500	69,000	1190	84	⊙	
11–4	290,500	48,000	1280	115	⊙	
11–6	235,500	59,000	685	60	⊙	
11–7	260,500	71,000	1190	112	⊙	
11–16	439,500	206,000	1945	212	△	
11–23	207,500	22,000	1030	99	⊙	
11–27	235,500	46,000	1040	167	⊗	
12–13	243,000	47,000	690	138	⊙	
12–18	308,000	100,000	1230	96	⊙	
12–23	351,000	100,000	850	8	⊙	
			1926			
1–2	200,500	13,000	560	60	⊙	
1–15	207,500	17,000	1050	123	⊙	
1–16	237,500	52,000	1080	95	⊙	
1–18	207,500	5,000	930	88	⊙	
1–25	218,000	5,000	1050	64	⊙	
2–20	253,000	80,000	500	92	⊙	
2–28	200,500	3,000	800	112	⊙	
3–23	379,500	157,000	620	61	⊙	
3–25	464,500	221,000	140	Disconnect Eagle Rock	⊠	
3–27	440,000	207,000	780	Cable Break 18	⊠	
4–5	284,000	81,000	990	150-kv. bus Eagle Rock	⊠	
4–22	440,000	194,000	462	68	⊙	
4–22	440,000	190,000	780	68	△	
5–1	366,500	138,000	2110	226	⊙	
5–16	391,000	88,000	650	15	△	
5–25	305,000	126,000	500	34	⊙	
6–29	479,500	255,000	920	4	⊙	
6–29	479,500	243,000	630	4	⊙	
7–15	440,000	148,000	1940	Vestal	⊙	
7–30	263,000	52,000	850	Vestal	⊙	
8–12	479,500	218,000	1870	61	⊙	
9–1	225,500	60,000	2370	212	⊗	
10–1	217,500	37,000	1890	210	⊗	
10–20	416,500	150,000	1570	87	⊙	
10–25	416,500	117,000	2180	209	⊙	
11–5	348,500	47,000	1470	173	⊗	
11–11	267,500	10,000	1020	33	⊠	
11–13	252,500	19,000	1940	170	⊙	
11–28	346,500	87,000	1330	91	⊙	
11–30	364,000	87,000	2780	238	⊙	
12–6	384,000	90,000	1620	169	⊙	
12–8	366,500	119,000	1620	140	⊙	

TABLE III—*Continued*

Date	Connected kv-a.	Big Creek generation	Total ground amperes	Location of fault	Relay operation	System operation
			1926—*Continued*			
12–9	457,500	192,000	2100	233	⊙	*
12–11	440,000	176,000	1545	150	⊙	
12–17	427,500	233,000	1340	182	⊙	
12–26	298,000	67,000	1460	163	⊙	
			1927			
1–4	. .	97,000	1670	163	⊙	
2–18	. .	114,000	1320	32	⊙	
2–22	. .	70,000	. .	. .	⊙	
5–1	. .	141,000	2760	Not found	⊠	

Correct relay operation....... ⊙
Incorrect relay operation...... ⊠
Partial relay operation........ ⊗
Relays not in service........... △
System interruption............. *

outages has been due to 220-kv. flashovers occurring at different loads. Curve *A* shows this relation in which outages from all causes are included. In Curve *B*, only those cases in which perfect relay action was secured are included. The difference between the two curves is principally accounted for by incorrect relay operation and operation with relays not in service.

It will be seen that for loads below approximately 150,000 kw., the probability of outage is very small and has been zero when the relay operation has been perfect. The Line *C* in Fig. 7 has therefore been drawn to this value. By reference to the load and flashover curves of Fig. 7, it will be noted that during the period in which loads in excess of 150,000 kw. are transmitted, the number of flashovers is small resulting in few actual outages. For this reason, the system can economically be operated at a high rating without serious possibility of outage.

The 220-kv. system has been caused to fall out of step due to troubles originating on the 60-kv. lines, the relation between the percentage of outage and transmitted load being similar, in a general way, to the curve shown by Fig. 8. It has been found that by setting the relays on the 60-kv. system adjacent to Eagle Rock and Laguna Bell for short time tripping, the communication of these troubles to the 220-kv. system has been very greatly reduced.

Recording Apparatus

The instruments used during these tests were not designed for continuous operation, but were arranged to be cut into service whenever a ground current flowed on the 220-kv. system, due to a line-to-ground fault. The general plan of the initiating equipment of an automatic recording instrument control, is shown in Fig. 9. An induction type relay, *A*, is connected to operate whenever current flows in the neutral of the main transformer bank at the station. This relay is set so as to operate in about one-tenth second with an average value of ground current. Its contacts complete the circuits of several auxiliary relays, which connect the different elements of the recording apparatus into circuit. The contacts of one of these auxiliary relays parallel the initiating relay contacts, locking the circuit

so that the instruments continue to operate even though the fault current has ceased. After a period of about 25 sec. another relay, *B*, short-circuits the holding coil of the lock-in relay, causing it to open and disconnect the apparatus. Wherever possible, the required power was taken from a source independent of the main system, so that the instruments would continue to operate even though there was a service interruption.

The various quantities measured are as follows:

1. Power into or out of station
2. Ground current
3. Bus voltage
4. Hydraulic gate opening.

The installations were made at a number of remotely separated points on the system in order to record the changes taking place at different parts of the system, and also to insure getting at least one record for each disturbance. This was rendered necessary because a short circuit at one end of the system did not always

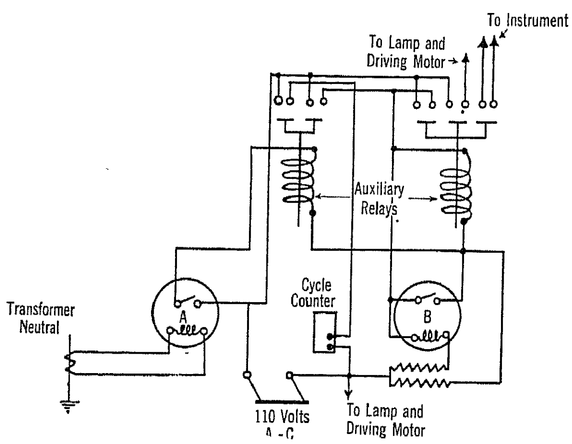

FIG. 9

give a sufficiently large current at the other end of the system to operate a ground current relay.

BIG CREEK NO. 3

Two specially designed high-speed graphic wattmeters are installed in this station for recording the total station output during transients, a wattmeter being connected on the low-tension side of each of the two power transformers. As shown by Fig. 1, one records the variation in output of two of the generators, and the other measures the output of the third generator in this station. In order to record the hydraulic input to one of the generators (unit No. 3), a mechanical recording device was fastened so that it recorded the position of the turbine gates. This device was calibrated in terms of the corresponding electrical output of the generator for steady load conditions. Each of the three charts was driven by means of a synchronous motor, operated from a house generator, so that corresponding times on the three records are known.

VESTAL

A Westinghouse three-element, permanent magnet type oscillograph is installed at the Vestal substation. Two standard elements are used to measure the ground currents flowing in the two 220—150-kv. auto-transformer banks. The third element is a wattmeter and records the power input to the 50-cycle side of one of the frequency changers. This element has a natural period of about 1/20 sec., making it suitable for recording rapid fluctuations of power.

EAGLE ROCK

The quantities on which measurements were made at Eagle Rock were the power to and from the Big Creek lines, the true power variations of one of the synchronous condensers, the ground current, and the voltage on the 60-kv. bus. The connections at this station were such that it was impossible to obtain a direct reading of the total incoming power, but since the transformers are paralleled on both the 220-kv. and 60-kv. sides, it was felt that sufficiently accurate power measurements would be obtained by measuring the power flow of one bank on the low-tension side, and multiplying by the ratio of the whole load to the load taken by this transformer. For this purpose a polyphase type of oscillograph wattmeter, having a natural period of about 1/20 sec., was employed. A similar wattmeter was used to record the variation in true power to one of the 30,000-kv-a. synchronous condensers. The totalized ground current of the two banks of auto-transformers was measured by means of a standard permanent magnet type of oscillograph element. An auxiliary relay was used so that after the ground current had ceased to flow, this element was transferred to measure the voltage on one of the low-tension buses. The recording apparatus at this station was arranged to operate upon the occurrence of either a 220-kv. or a 60-kv. ground. A cycle counter was used to measure the total duration of the ground current, subject to a slight error due to the time required for the initiating relay to operate.

LAGUNA BELL

The output of one of the 220/60-kv. step-down transformers at Laguna Bell is measured by a high-speed graphic wattmeter of a type similar to that used at Big Creek No. 3.

BIG CREEK NO. 1

An additional installation was recently made at Big Creek No. 1, consisting of a single wattmeter element oscillograph, having a natural period of about 1/3000 sec., so that power variations within the cycle are recorded. This installation has been in service but a few months and has not operated frequently due to the small magnitude of the ground currents at this station.

TYPICAL RECORDS

During the period in which the automatic recording

apparatus has been installed, records have been obtained on about 65 flashovers. Of these, no two are exactly alike, since they involve different system setups, different loads, and different type and location of fault. Consequently from the large number of records available, it has been necessary to select a few which may be taken as typical of the different conditions that may occur in practise. The total synchronous kilovolt-amperes listed refer to the capacity connected at Big Creek, Vestal, Eagle Rock, and Laguna Bell.

At the time this flashover took place, there was no automatic protection in case a short circuit occurred on the 150-kv. bus, except that provided by the operation of the flashover suppressors; consequently the short circuit continued for several minutes. The records were taken at Big Creek No. 3, and show the combined output of generators No. 1 and No. 2, the output of, and hydraulic input to generator No. 3. The first two seconds of the record is omitted since there was little variation during this period. At about three seconds after the beginning of the short circuit, the power output at Big Creek No. 3 begins to fluctuate slightly, the rapidity of the fluctuations gradually increasing. This is probably due to the generators at Big Creek No. 1 pulling out of step with the rest of the system owing to the reduction in their field currents by the action of the flashover suppressors. After having thus pulled out of step, the mean output of Big Creek No. 1 is very small, and the loss of this generating capacity allows the system as a whole to drop in frequency. This causes the governors at Big Creek No. 3 in an attempt to regain normal frequency, to open up as shown by the record of gate opening of the No. 3 unit. Meanwhile, the arc suppressors at Big Creek No. 3 have also functioned, making the generators in that plant incapable of sustaining their load, and they also pull out of step, as evidenced by the rapid reversals of power. Each reversal in the direction of power flow means that the generators at Big Creek No. 3 have slipped a pole with respect to the rest of the system, and that they are overspeeding. The hydraulic input to the generators is then decreased by the action of the governor until normal frequency is regained. The remainder of the

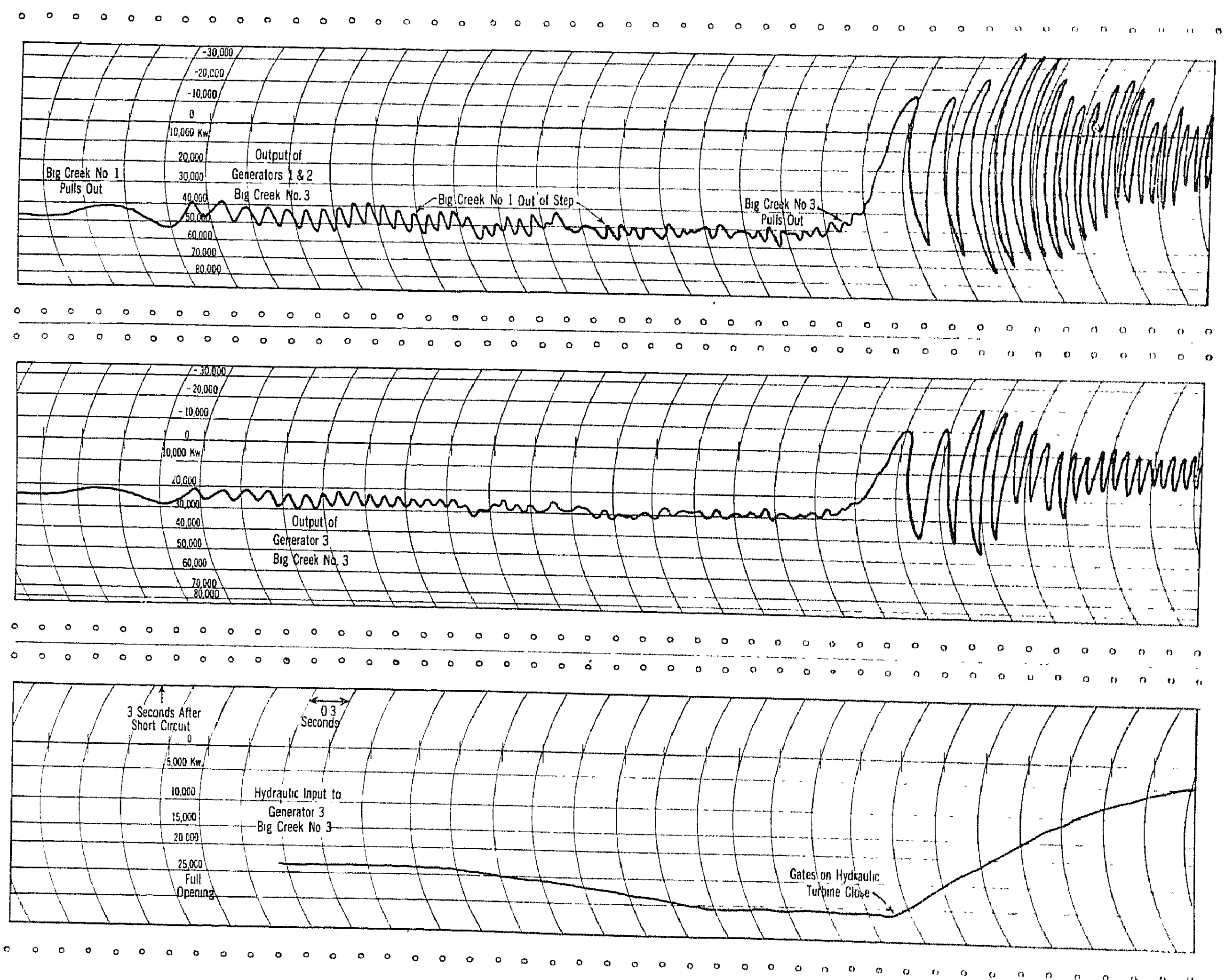

FIG. 10—(SEPTEMBER 3, 1925). FLASHOVER ON 150-KV. BUS AT BIG CREEK NO. 1. BIG CREEK GENERATION, 201,000 KW. TOTAL SYNCHRONOUS KILOVOLT-AMPERE, 424,000

charts (not shown in the illustration), shows the clearing of the short circuit and subsequent building up of load. During this period, there was considerable hunting of the governors.

This case may be taken as illustrative of the operation of the system without automatic line protection and with a large, transmitted load. At the time the short circuit occurred one of the 27-mi. lines, between Eagle Rock and Laguna Bell, was out of service, so that the balanced line relay protection could not be left in service. Therefore, the flashover suppressors at the various stations operated to reduce the machine excitations until the arc broke. Before this happened, however, the system pulled out of step owing to the reduction in voltage, and partly because the action of the governors at the Big Creek Plants had increased the total generation to meet the demand made by the short circuit. An important point brought out by these records and those of Fig. 10 is that there is no tendency for the generators in a given plant to lose synchronism with each other so long as the generators as a group remain in synchronism with the rest of the system. It will be noted, however, that when they pull out from the system, there is a tendency also to lose synchronism between generators.

Fig. 12 group of records A, B, and C, taken at Big Creek No. 3, is typical of 220-kv. flashovers not resulting in loss of synchronism. Automatic protection was in service and perfect relay operation was secured. In the cases of the first two of these flashovers, the total transmitted power was about 150,000 kw. for the two circuits, which should cause no difficulty from the stability standpoint. In the third case, however, the power generated at Big Creek was 218,000 kw. and the successful clearance of a fault at this load is excellent performance,—particularly since it involves dropping a 100-mi. section of line. Note that the high-frequency oscillations at the beginning of two of these records are mainly due to inertia of the pen mechanism.

The flashover, Fig. 13, was over a 150-kv. bushing at Eagle Rock; hence the greater part of the short-circuit current circulated through the station grounding network without the inclusion of any earth contact resistance. This low resistance type of short circuit differs from the

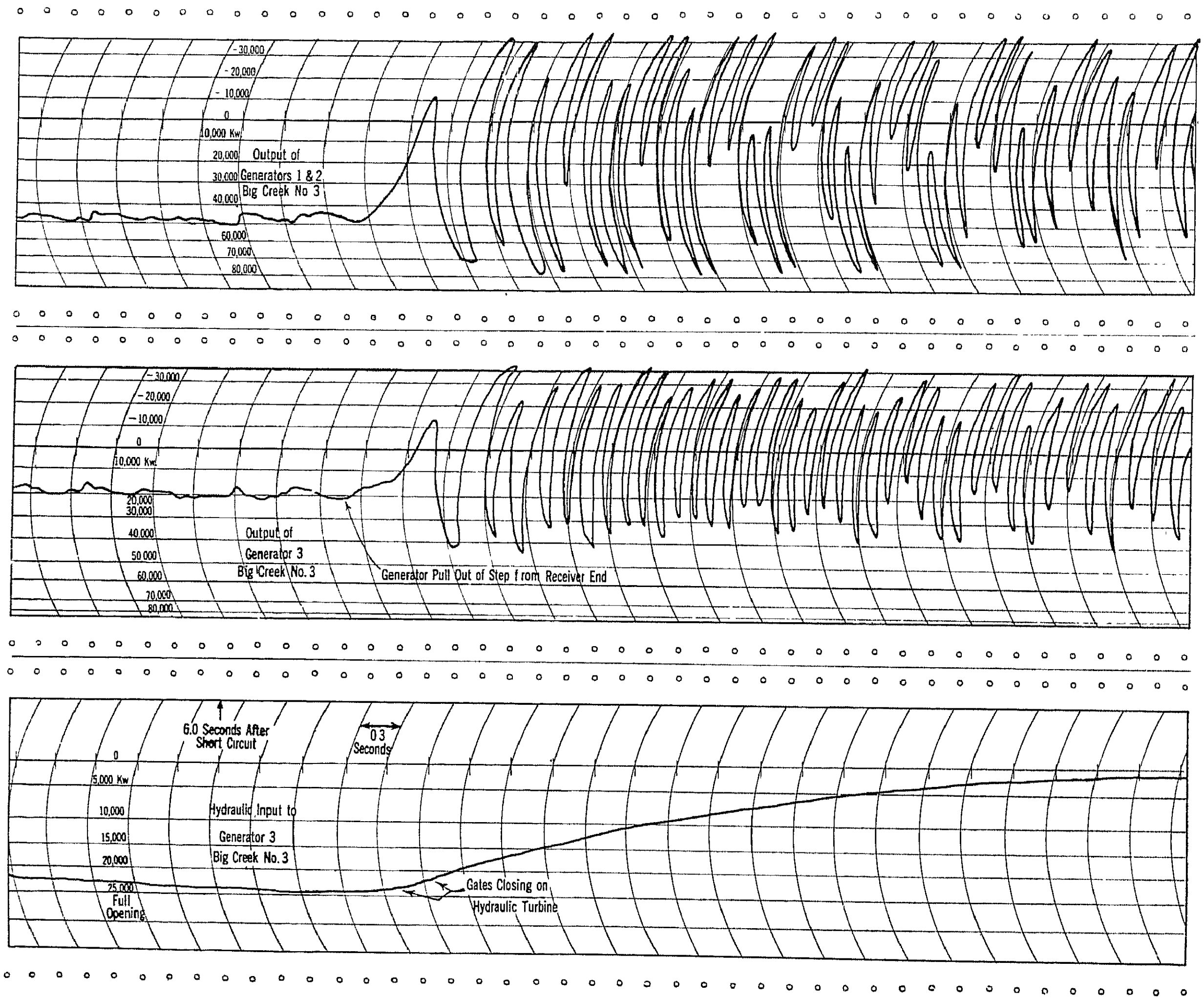

Fig. 11—(November 16, 1925). 220-kv. Flashover at Mile 212. Total Big Creek Generation, 206,000 Kw. Total Synchronous Kv-a., 439,500

usual type experienced on the transmission line, since practically no power is consumed by the fault itself, while the system load is probably decreased because of the greatly reduced voltage in the part of the system near the fault. The sudden loss of load allows the system frequency to increase somewhat, thus causing the governors on the Big Creek machines to cut off water as shown by the record from No. 3 unit at Big Creek No. 3. As in the case of the bus short circuit at Big Creek No. 1, the flashover suppressors were relied upon to clear the fault, which they were able to do without causing the system to pull apart, since the transmitted load was but 81,000 kw. Total synchronous kv-a., 284,000.

Two records, Fig. 14, from Big Creek No. 3 afford an excellent illustration of the necessity for prompt isolation of a faulted line. The first flashover was caused by a hay derrick under the line, which was readily cleared by the relays and the line put back in normal service. About two hours later, in order to move the derrick, the line was made non-automatic prior to being taken out of service. But the derrick again short circuited the line while it was thus without automatic protection, and before being de-energized. It will be noted that barely three seconds elapsed before the generators pulled out of step, showing that any relay system to be adequate, must operate in a very short period of time.

In this particular case, in some unknown way, one of the wattmeter coils was inoperative, the instrument giving a single-phase reading only, which accounts for the small amount of power indicated after the short circuit was cleared. The actual amount of power at that time was close to 60,000 kw. The charts, however, serve the purpose of showing the difference in the operation with and without automatic protection.

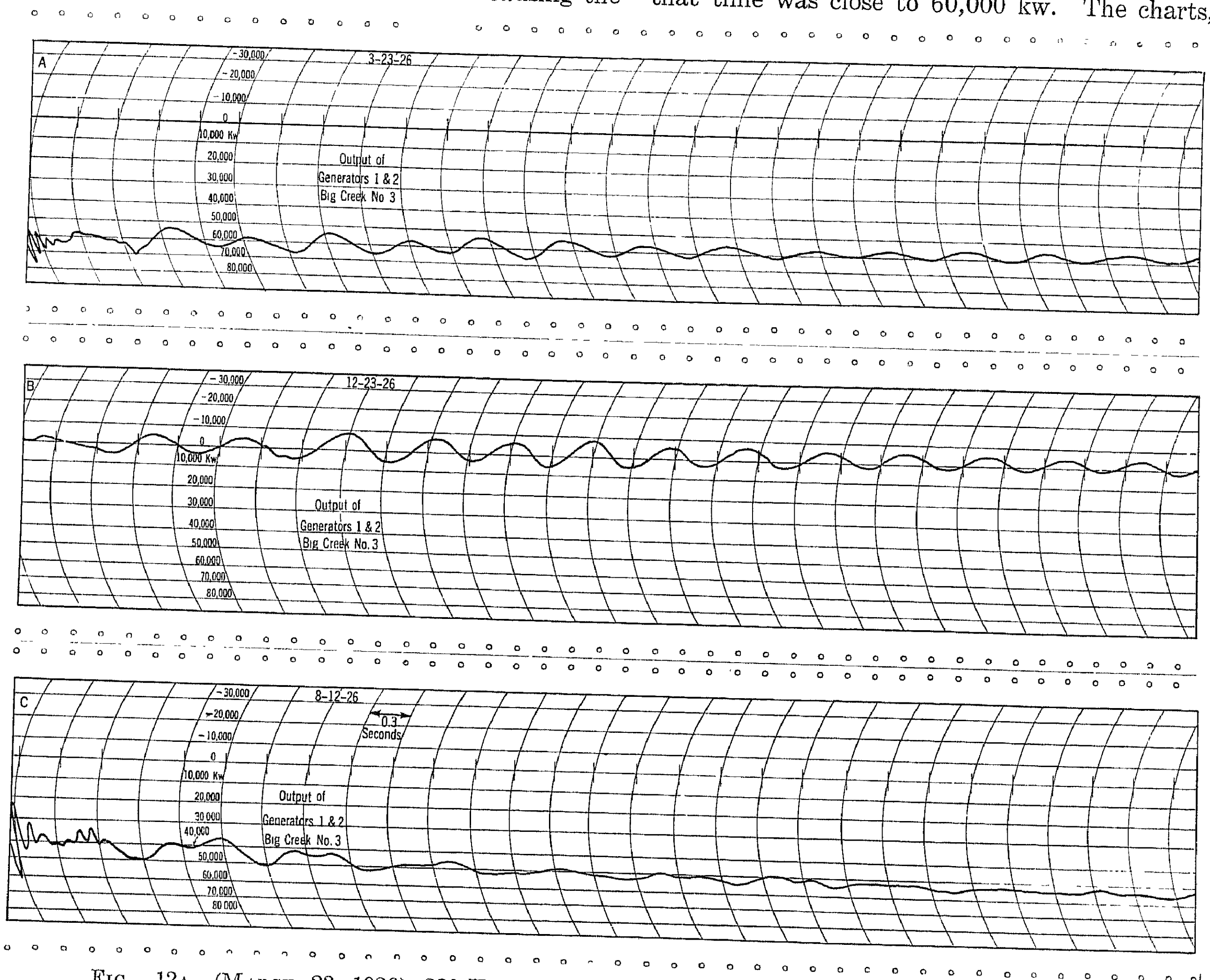

FIG. 12A—(MARCH 23, 1926). 220-KV. FLASHOVER AT MILE 61. TOTAL BIG CREEK GENERATION, 157,000 KW. TOTAL SYNCHRONOUS KV-A., 379,500
B—(DECEMBER 23, 1925). 220-KV. FLASHOVER AT MILE 8. TOTAL BIG CREEK GENERATION, 100,000 KW. TOTAL SYNCHRONOUS KV-A., 351,000
C—(AUGUST 12, 1926). 220-KV. FLASHOVER AT MILE 61. TOTAL BIG CREEK GENERATION, 218,000 KW. TOTAL SYNCHRONOUS KV-A., 479,500

This flashover, Fig. 15, occurred at a time when the transmitted load was fairly high, and, in addition, the fault resistance was of such a value as to cause a large amount of power to be consumed. This combination of circumstances was such as to cause loss of synchronism despite the fact that the line was relayed out correctly. The oscillographs from both Eagle Rock and Vestal showed that the generators had commenced to pull out

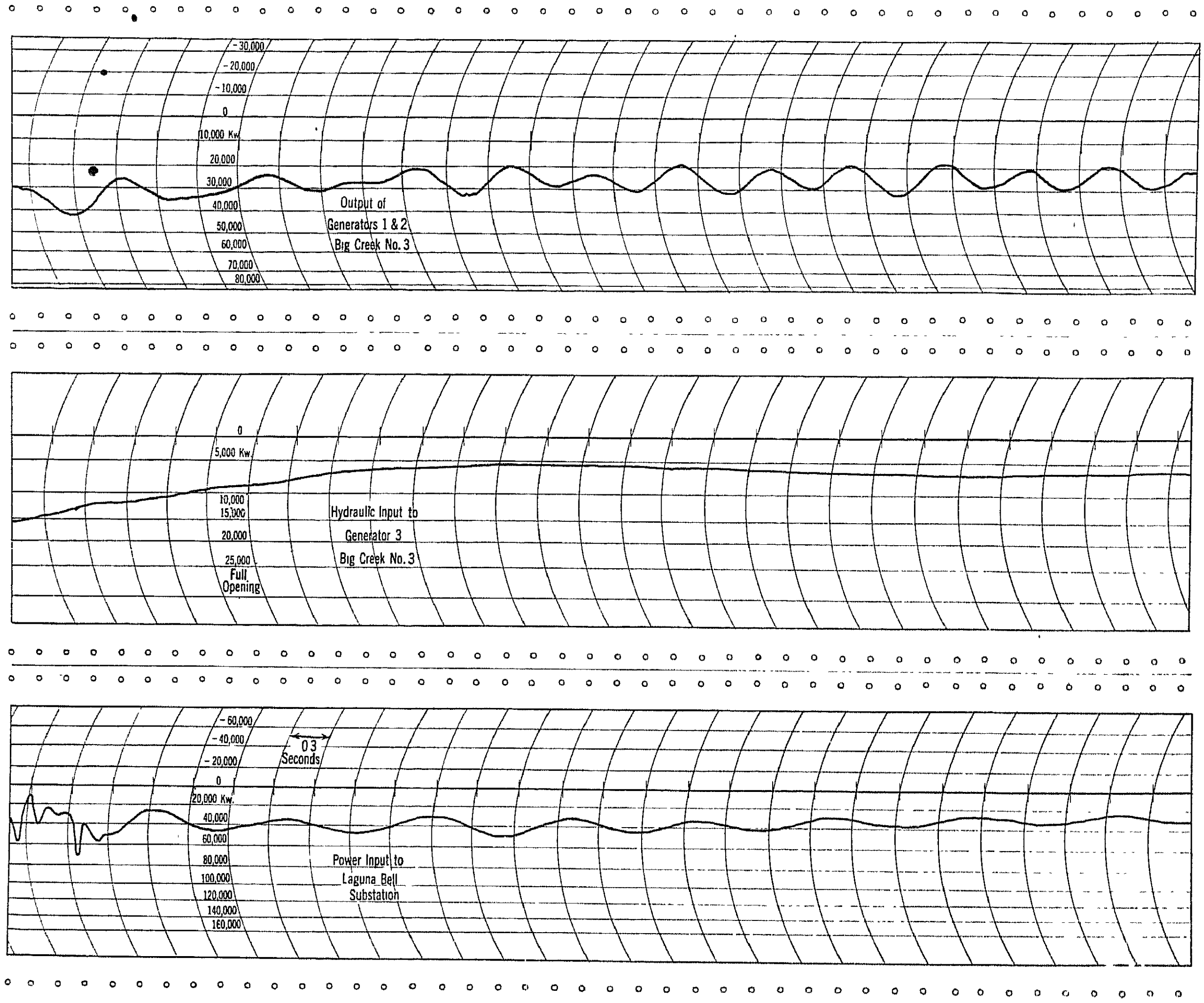

FIG. 13—(APRIL 5, 1926). FLASHOVER ON 150 KV. BUS AT EAGLE ROCK. TOTAL BIG CREEK GENERATION, 81,000 KW. TOTAL SYNCHRONOUS KV-A., 284,000

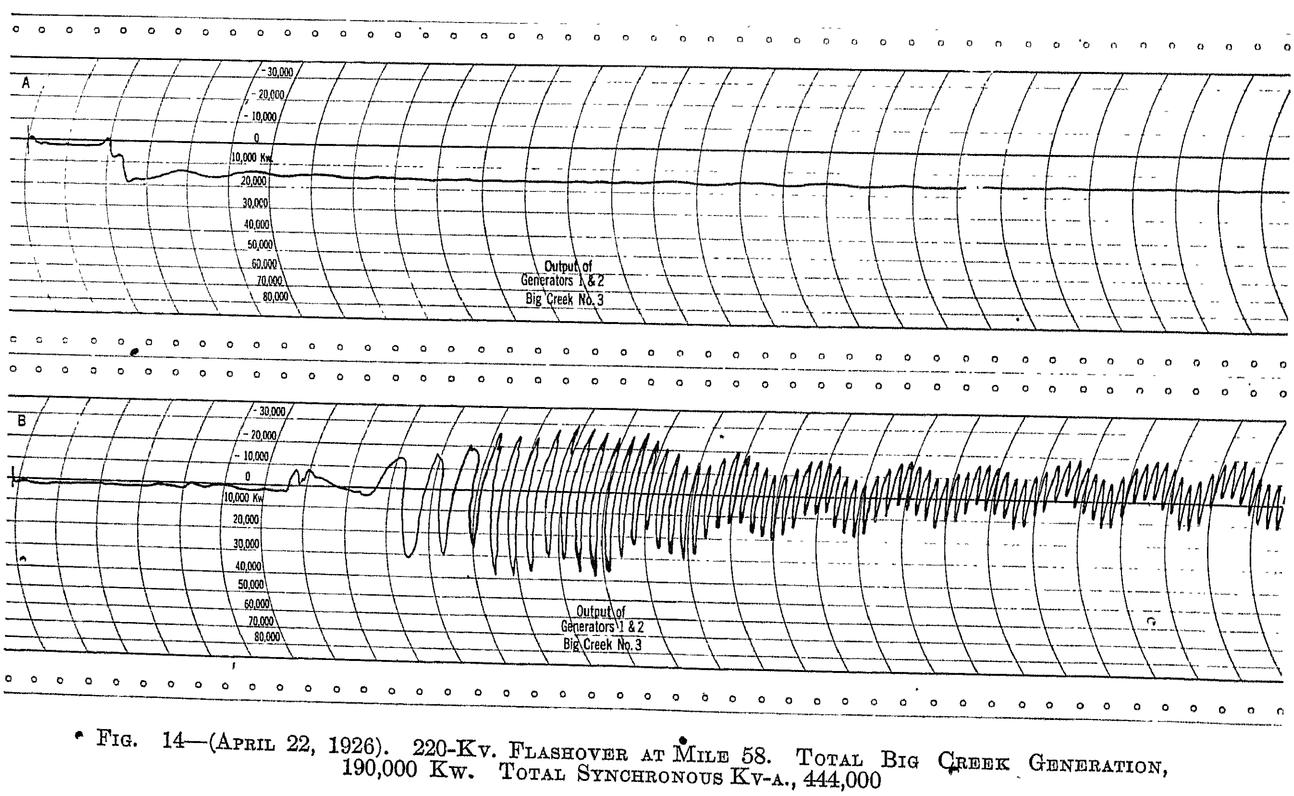

FIG. 14—(APRIL 22, 1926). 220-KV. FLASHOVER AT MILE 58. TOTAL BIG CREEK GENERATION, 190,000 KW. TOTAL SYNCHRONOUS KV-A., 444,000

of step within three-fourths second after the beginning of the flashover. (The first visible cycle on the oscillograms taken at Eagle Rock and Vestal are about 20 cycles after the start of the short circuit due to the time lag of the relays and the oscillograph lamp.) The variation in magnitude of the ground current is due to the change in voltage as the Big Creek machines shift in phase position with reference to each other and to the

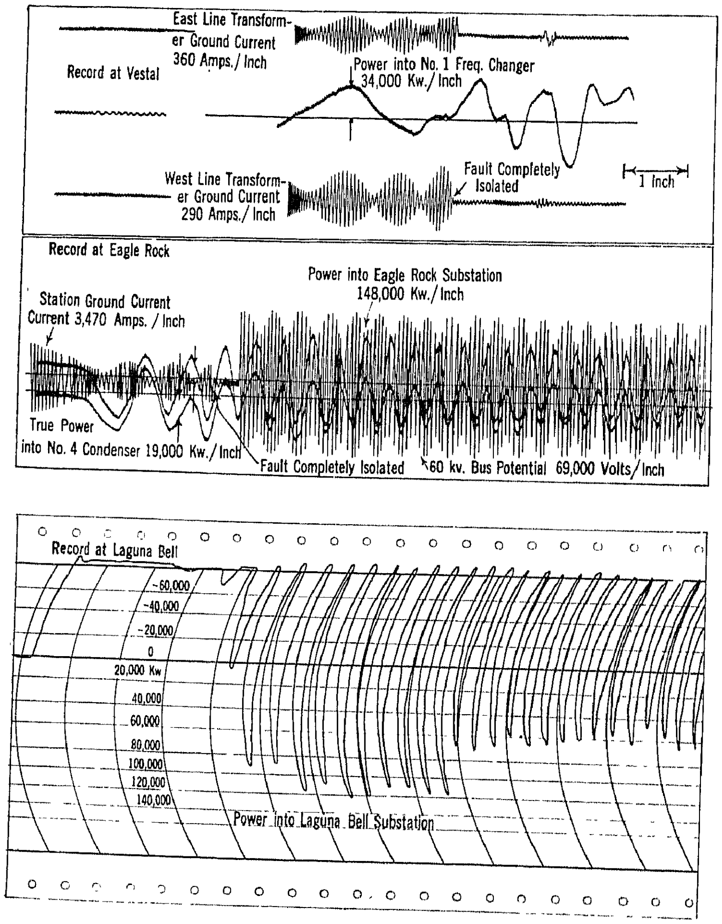

FIG. 15—(DECEMBER 9, 1926.) 220-KV. FLASHOVER AT MILE 233. TOTAL BIG CREEK GENERATION, 192,000 KW. TOTAL SYNCHRONOUS KV-A., 457,500

remainder of the system. The first visible part of the record shows that the ground current first decreases and then pulsates in amplitude indicating that the phase position of the Big Creek machines has advanced beyond the point corresponding to the maximum power limit. The enormous amount of energy consumed by this flashover is shown by the records from Laguna Bell and Eagle Rock. While the short circuit lasted (about 1.5 sec.), the power fed out of the Laguna Bell substation was over 90,000 kw. (this is the maximum the instrument could record in this direction), while the amount of power originally fed into this substation was 74,000 kw., a difference of over 164,000 kw. The original amount of power into the Eagle Rock substation was 120,000 kw., dropping to 30,000 kw. when the flashover struck. Therefore the total Big Creek power to the two receiving stations changed from 194,000 kw. in, to 60,000 kw. out, when the flashover occurred, a difference of 254,000 kw. No record was obtained of the corresponding variation in Big Creek power, but it is probable that it dropped somewhat momentarily owing to the comparatively low resistance of the fault and the high reactance of the 233-mi. of line.

It will be noted that a greater variation in power took place at Laguna Bell than at Eagle Rock. This is undoubtedly due to the fact that the Long Beach steam plant is more closely connected to the Laguna Bell substation so that most of the power fed to the fault from Long Beach went through Laguna Bell.

Fig. 16 shows oscillograms typical of those obtained where the system does not pull out of step with a 220-kv. flashover. The drop in voltage is very slight even while the short circuit is on, and it immediately regains its original value after the short circuit is cleared. Except for this slight drop in voltage and small power surges, there is no system disturbance. The oscillogram taken at Eagle Rock furnishes a good illustration of the successive opening of circuit breakers as shown by the changes in ground current. Owing to the line connections employed, it is necessary for the breakers at three points to open to clear a fault in the section where the flashover occurred, increasing the total time required before the fault could be entirely cleared.

The short circuit, Fig. 17, occurred on one of the 60-kv. feeders out of the Eagle Rock substation. The last breaker to completely isolate the faulted line probably

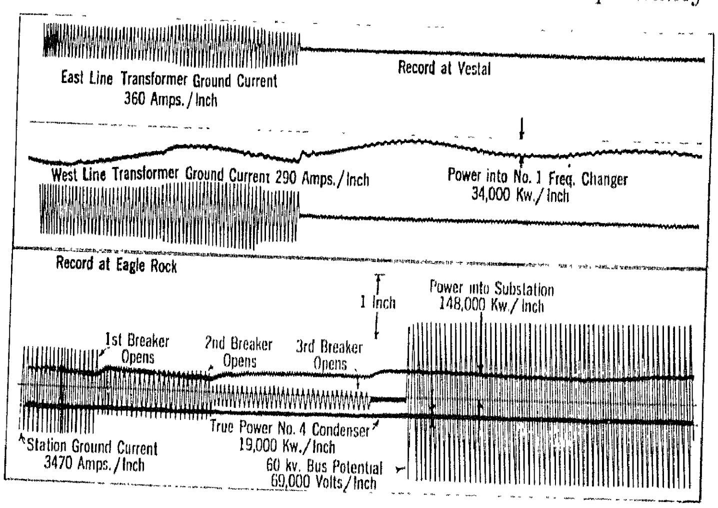

FIG. 16—(NOVEMBER 30, 1926). 220-KV. FLASHOVER AT MILE 238. TOTAL BIG CREEK GENERATION, 78,600 KW. TOTAL SYNCHRONOUS KV-A., 364,000

opened at the point marked A. The Big Creek generators have already advanced beyond the point where recovery is possible, and pull-out results. In this case, the power surges back and forth between the Big Creek end of the system and the receiver end, with a surge of about plus or minus 100,000 kw. at the Eagle Rock substation. The variations at Laguna Bell are probably at least equal in magnitude, so that the total resultant power surge is probably of the order of 200,000 kw. in each direction. During this condition

of slip between the two ends of the system, the mean power interchange is zero except for the line losses which are, in the main, supplied from the end running at the higher frequency (in this case the Big Creek machines).

The amplitude of voltage at the Eagle Rock substation varies at the slip frequency, as shown by the oscillogram. The fact that the fluctuations in synchronous condenser power occur at this same frequency shows that the condensers are maintaining synchronism with the bus to which they are connected, and are not,

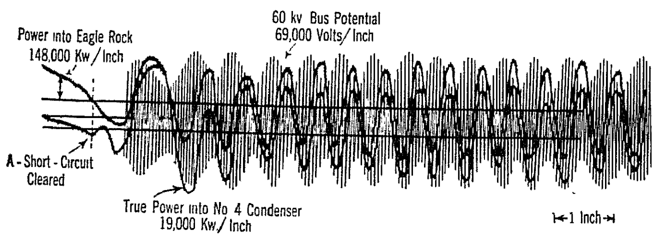

FIG 17—(JULY 31, 1926). 60-KV. SHORT CIRCUIT NEAR EAGLE ROCK. TOTAL BIG CREEK GENERATION, 205,000 KW. TOTAL SYNCHRONOUS KV-A., 439,500.

themselves, out of step. No instances have been recorded in which synchronous condensers have gone out of step with the station bus voltage.

Fig. 18 gives a record included for the purpose of showing the type of the disturbance caused by a 60-kv. short circuit near McNeil substation, not resulting in loss of synchronism. The voltage on the 60-kv.. bus dropped appreciably while the short circuit was on, but quickly regained its normal value

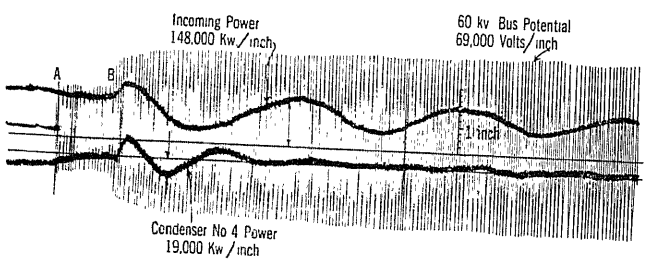

FIG. 18—(FEBRUARY 15, 1827). 60-KV. SHORT CIRCUIT NEAR McNEIL SUBSTATION. TOTAL BIG CREEK GENERATION, 127,000 KW.

with very slight fluctuations accompanied by a surging of power from the Big Creek system. The breaker on the end of the line nearest to Eagle Rock probably opened at point A, reducing the ground current required below that to hold the initiating relay closed. The measurement of the 60-kv. bus potential starts at this time, the voltage being about half of normal until the short circuit is completely cleared at B.

DISCUSSION OF INDIVIDUAL FACTORS AFFECTING STABILITY

Out of a total of 65 disturbances taking place during the period that automatic recording apparatus was installed, there were practically no cases in which the system set-ups were identical or in which character of faults were the same. Consequently, it is not possible to make a direct comparison of some of the factors without the use of a certain amount of supplementary theory to place the cases on a common basis. The purpose of the following section is to isolate some of the factors affecting stability, and to analyze them individually, drawing upon the test results as much as possible.

TYPE OF FAULTS

The 220-kv. disturbances occurring between August, 1925, and May, 1927, are as follows:

220-kv. line to ground	59
Station bus to ground	4
Conductor-break	1
Open disconnect	1
	65

These faults occurred in almost every possible combination. They included high-resistance faults at many points on the 220-kv. lines, low-resistance faults on the 150-kv. buses at the ends of the line, and occurred at times of widely varying loads; also, the operations have included those in which normal relay protection was in service and other cases in which the lines for maintenance work or otherwise were operated non-automatically. As shown by the tabulation, all but two of the faults were single-phase short circuits to ground, the protection for which should be made the basis of design. In this connection, it should be pointed out that although very few records were obtained from faults on the 60-kv. network, the number of faults on this network exceed those on the 220-kv. system. With the initiating relay scheme used, only the 60-kv. faults near the Eagle Rock substation were recorded. So far as the stability of operation of the 220-kv. system is concerned, only the 60-kv. faults occurring close to the Eagle Rock or Laguna Bell Substations are of importance. For these reasons, most of the subsequent discussion will be devoted to line-to-ground faults on the 220-kv. lines, and those line-to-ground faults on the 60-kv. system, close to the receiving substations.

LOCATION OF FAULTS

The location of a fault affects the stability of the system in two ways: (1) according to the amount of synchronous equipment and load in proximity to the fault, and (2), in so far as the local conditions affect the resistance of the fault. In order to evaluate the effect of the first, a set of curves was calculated to show the theorectical variation in the voltage, current, and power relation for faults of different resistance and locations. These curves were based on two-line operation with a single-phase ground on one line. A representative system condition was approximated by taking an average capacity in generators at the two ends of the line. Certain simplifying assumptions were made to facilitate calculations, the resistance of the lines and station ground being neglected and the generator voltages being assumed equal and in phase. The curves of Fig. 19 show the variation in total fault current

against location of fault for different fault resistances. With zero fault resistance, the current varies from about 2000 amperes in the middle of a section, to about 3000 amperes at either end. As the assumed resistance of the fault is increased, the variation due to location becomes less marked until, with 100 ohms resistance, the magnitude of the current is practically independent of the location. In order to get an approximate idea of the range of fault resistances actually encountered in practise, the values of total fault current obtained for different flashovers are plotted on this diagram. Graphic recording ground ammeters are used in all of

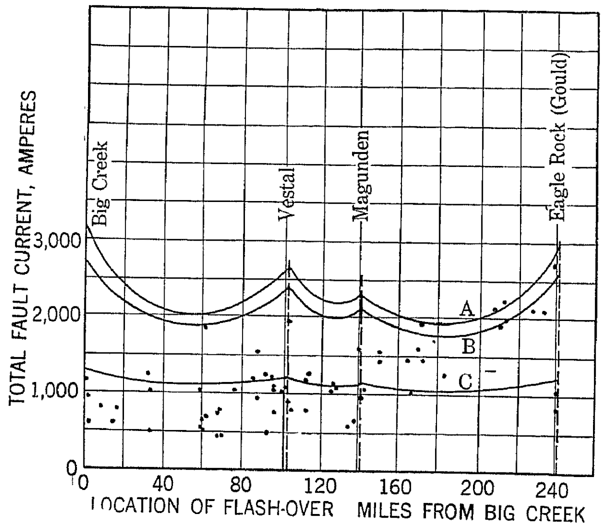

FIG. 19—VARIATION IN FAULT CURRENT WITH PHASE-TO-GROUND FLASHOVERS AT DIFFERENT LOCATIONS

A—Zero fault resistance
B—25 Ohms fault resistance
C—100 Ohms fault resistance

the 220-kv. generating and substations, and the sum of the readings of these ammeters was used to indicate the total fault current. The values thus obtained are not very accurate, since the ammeters were not of a type suitable for accurate measurement when the current was of short duration, and because the arithmetical rather than the vector sum was obtained. However, for purposes of comparison, it is believed that the figures are sufficiently reliable, particularly since, with so many readings to be added, the individual errors would tend to cancel out. By comparing the observed and calculated values, it will be noted that the actual fault resistance varies from about 25 to 250 ohms. The lower values of fault resistance are found near the region of the receiving end of the system, and the higher values toward the sending end. This difference can be explained by the character of the country through which the transmission lines pass. The generating stations are located in a region of rocky formation where the water is very pure and the ground resistance is high the year around. The upper part of the transmission lines also passes through this region. The middle and part of the lower section of the transmission lines passes across the San Joaquin Valley, the surface soil of which, for a large part of the year, is dry. For this reason the resistance at the point of accidental ground, such as at a transmission line tower, is quite high, even though the towers are connected by means of an overhead ground wire. The lower portion of the transmission lines is located nearer the Coast, where the soil does not become thoroughly dried out, giving a lower contact resistance. As mentioned above, the calculated curves were based on the assumption of zero ground resistance at all stations. Owing to the character of the soil at Big Creek and Vestal, the resistances at these stations are probably too high to be neglected, and there is probably a certain amount of error due to this assumption for these stations.

The flow of current through the fault resistance causes a very considerable power demand upon the system, which must be supplied by the generators at the two ends. Fig. 20 shows the calculated variation in the power consumed by a fault of 100 ohms resistance, according to its location on the system. Curve A shows the total power, Curve B, the portion supplied by the Big Creek generators, and Curve C that portion supplied by the generators at the receiving end of the system. From these curves, it will be noted that, with a fault close to the sending end, most of the power loss will be taken by those generators, while if the fault is located near the receiving end, the greater proportion of it is taken by the receiver generators. This division of the power increment due to the short circuit may be quite important. With a given relation between the

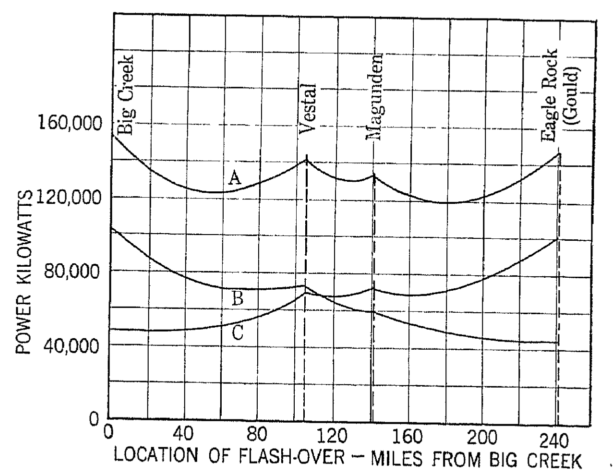

FIG. 20

total stored energy of rotation for the machines at the two ends of the system, the division of the power increment will determine the initial tendency toward shifting in phase position. For instance, suppose that the kinetic energy of the receiving end machinery is twice that at the sending end. For the condition for which the curves of Fig. 20 are drawn, and with the short circuit at the receiver end, 100,000 kw. of the increment of load due to the short circuit is taken by the receiver generators, and about 50,000 kw. is taken by the sending generators. Both ends of the system

will therefore slow down at the same rate, and there will be very little, if any, change in their relative phase positions; consequently, when the fault is eventually isolated, the disturbance will be slight. As the other extreme—if the short circuit occurred near the sending end, the sending generators would slow down about four times as rapidly as the receiving generators, and a considerable oscillation would result, depending upon the time in the period of oscillation at which the circuit breakers opened. No direct evidence bearing upon this point was obtained from the records, but it should be pointed out that when the Big Creek system is heavily loaded, the generating capacity at the receiver end is relatively low, making the kinetic energy of the machines at the two ends of the line of about the same order, a condition favorable to preventing large oscillations.

Fault Resistance

As indicated by the Curves of Fig. 19, the fault current is determined very largely by the fault resistance

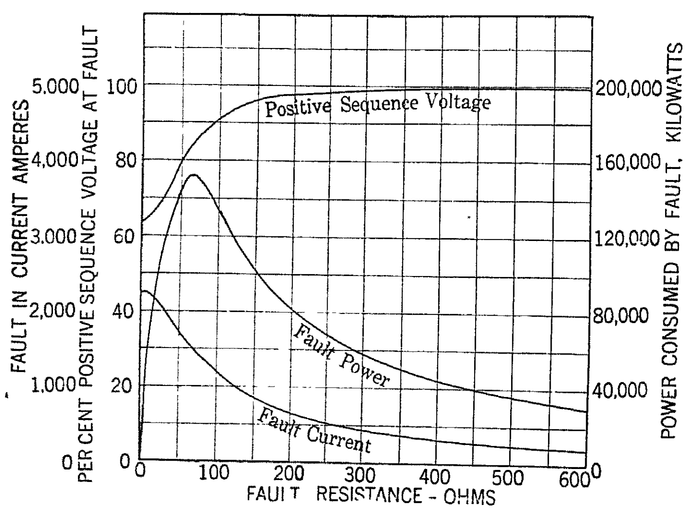

Fig. 21

when it is above approximately 25 ohms. The relation between the curves and the points obtained from ground current ammeter readings indicate that the fault resistances vary considerably, ranging from about 25 to 250 ohms. This value of ground resistance is very important in its effect on the system as is shown by Fig. 21 which gives the different fault resistances for phase-to-ground fault at Magunden substation. The two most important quantities from the standpoint of stability are the reduction in voltage and the increase in power demand caused by the short circuits. Between 0 and 50 ohms, the positive sequence voltage varies from 64 per cent to 80 per cent, while the power demand varies from 0 to 150,000 kw. These curves were calculated for a short circuit at Magunden, and this range of resistance is the most critical for this point. Between 50 and 100 ohms, ground resistance, the power demand due to the short circuit is practically unchanged, while the positive sequence voltage rises from 80 to 92 per cent. Although the results to the system are not so severe within this range as at the lower resistances, it is also rather a critical one, owing to the high power demand. Beyond 100 ohms, the power demand falls off rapidly, while the positive sequence voltage remains at a high value, resulting in the least shock to the system. For short circuits at other locations, the maximum power demand would be considerably increased. The commercial load on the system is also changed by the short circuits, depending upon the drop in voltage and its duration.

The enormous amount of power consumed by a single phase ground is well brought out by the record from Laguna Bell shown by Fig. 15. In this case the power taken by the fault was sufficiently great to change the power flow at the receiving substations from 194,000 kw. flowing in, to over 60,000 kw. flowing out. Assuming that the Big Creek power momentarily dropped by about 50,000 kw., due to the lower voltage at the receiver end, the indications are that about 200,000 kw. was consumed in the fault. When it is recalled that the total ground current during this flashover was over 2000 amperes, it will be seen that a fault resistance of only 50 ohms is necessary to account for the power in question. The effect of this load, suddenly thrown on and then suddenly released, was sufficient to cause the system to lose synchronism.

It should be noted that the conditions on the 220-kv. lines of the Southern California Edison Company are very favorable from the standpoint of fault resistance, since the very great majority are over 100 ohms in resistance, while the resistances which would cause the most disturbance are considerably lower in value. This fact should be borne in mind when estimating the probable performance of other systems by comparison, because if the fault resistances are low, poor operation may result even though the system is otherwise well laid out.

Owing to the great importance of ground resistance in determining the action of the system, it may in some cases be desirable to take special precautions to keep the resistance above the critical value by using high resistance overhead ground wires, resistance grounding of transformer neutrals with full, 220-kv. class insulation or some other method; whichever may be found to be most practical in any particular case.

Relay Operation

The importance of quickly isolating a fault was discussed to some extent in connection with the flashover of April 22, and December 9, 1926. In the case of the first two flashovers, a direct comparison between a rapid relay operation and no relay operation was obtained under practically identical circumstances. With the rapid relay and switch operation (about 1.2 sec.), it was possible to cut out a 100-mi. section of line while carrying 190,000 kw., and not drop out of step. A little later when the line was made non-automatic, the

system pulled out of step within three seconds after the short circuit occurred, showing that relay operation taking this length of time would not be effective for this particular set-up. In the case of the last flashover, the particular combination of high transmitted load and critical fault resistance was such that in order to have it effective, the total time for the relays and circuit breakers would have to be less than one-half second.

When a flashover occurs, the machines at the two ends of the system shift in phase position so as to conform to the new conditions. Due to their inertias, however, there is always a certain amount of oscillation. A similar tendency to shift in phase position exists when a circuit breaker opens to clear the fault, and the oscillation which this would tend to create may either add to or subtract from that already existing, with a corresponding influence on the system. There is thus an optimum time for the clearance of a given fault which is not necessarily the minimum time. Since no definite time of circuit breaker opening will be satisfactory for all cases, the best procedure is to obtain as quickly as possible an isolation of the fault. With the balance current type of relay used, it is possible to secure very rapid relay action, the minimum time being principally determined by the time required for the circuit breaker to open after being tripped.

Oscillographic measurements during a large number of flashovers give the following average times from the beginning of the short circuit for operation of circuit breakers. Straight line sections, (two breakers to completely isolate line), 0.75 sec. for first breaker to open; 1.2 sec. for last breaker. Tapped line, (three breakers to completely isolate line), 0.75 sec. for first breaker, 1.3 sec. for second breaker, and 1.7 sec. for last breaker.

Sequence of Circuit Breaker Operation

In practically every relay scheme now in use, it is necessary, under some conditions, for the circuit breaker at one end of the line to open before some other relay can operate. This means that the faulty line is not opened at both ends at the same instant, but that there is a time interval between the operation of the breakers at the two ends. Due to the setting of the relays, and the adjustment of the different breakers, this effect has been observed in every case. This effect is probably advantageous from the standpoint of stability, since it reduces the size of the changes necessary to drop the heavy load due to the fault, and resume the normal load. This point is illustrated by Fig. 16; the oscillogram taken at Eagle Rock during the flashover of November 30, 1926, where three circuit breakers opened one after another to finally isolate the faulty section of line. This oscillogram shows the abrupt change at the instant the breakers opened, and the gradual readjustment between this time and the time that the next breaker opened, so that when the last breaker opened, clearing the fault, there was comparatively little change required to resume the original load, and the power oscillations are small. An interval of time between breaker operation appears desirable, but the advantage of a gradual change would probably be overbalanced if the short circuit were permitted to hang on too long. For this reason, set-ups are avoided so far as possible which would too greatly prolong the time required to isolate the faulted section of line.

Length of Line Sections

Owing to the fact that other conditions had a greater effect, it is not possible to show from the records the influence of the length of line section on stability of operation. Other things being equal, however, it is probably safe to assume that the length of the section affects the working power limit of the line about inversely as the percentage increase in the total system impedance, (including generator and transformer reactance), caused by switching out the section.

System Layout

The primary factors governing the location and general arrangement of generating and substations are, of course, the location of the available power and the load. However, a certain amount of freedom is permitted in the case of the larger distributing substations, and these are, in general, located so as to avoid, as much as possible, too large a concentration of power. Complicated ties between stations are also avoided, so that in case of emergency, it will be possible to separate some of the sections from the main system with a minimum of switching. The synchronous condenser capacity required for line regulation and for power factor correction is divided between the various receiving substations, and the small substations near the load. One of the advantages of this arrangement lies in reducing the number of synchronous machines which may be affected by a given short circuit, thus reducing the area affected.

Simultaneity of Breaker Contact Opening

In some previous[4] tests reported on the action of 220-kv. breakers, it was found that in some cases, the difference in the opening of the three poles of the breaker was sometimes as much as 20 cycles, due to poor mechanical adjustment. During this interval, a ground current flowed. So far, there have been no instances shown by the oscillograms in the tests on the Edison system where there was any appreciable difference between the time of opening of the various poles of the breakers. When a 220-kv. line is opened, there is a voltage of appreciable magnitude induced in the communication circuits, but this is always of short duration, and has been satisfactorily cared for by means of saturating vacuum tubes in the telephone apparatus. The relay scheme, however, since it is of the balance current type, is not affected by residual currents of this kind.

4. *Practical Aspects of System Stability*, by Roy Wilkins, Trans. A. I. E. E., Vol. XLV, 1926, p. 41.

Reactance of Transformers and Machines

Owing to their nature, the tests could not show the value of low reactance in increasing the power limit of the system, but this point has been very well established by theory, and extensions of the system are being equipped with generators and transformers having reactances lower than the usual values.

60-kv. Short Circuits

On the Edison system, it has been the experience that short circuits on the 60-kv. network may be quite as detrimental to the operation of the 220-kv. lines as short circuits on the 220-kv. lines themselves if they occur close to the 220-kv. terminal substations. Fundamentally, short circuits close to terminal substations should differ but little in their effect upon the system whether they are on the 60-kv. or 220-kv. networks. Such differences as may actually exist must be due to conditions affecting the kilowatt and kilovolt-ampere demand on the system, and the duration. As pointed out in a previous section, the resistance of the majority of the faults on the 220 kv. lines is above the critical range owing to the character of the country through which these lines pass. On the 60-kv. network, the critical range of resistance is considerably lower, (approximately the ratio of the squares of the two voltages), but these lines pass through regions where it is known that the ground resistances are quite low. It appears probable, therefore, that the relatively greater severity of 60-kv. short circuits is, in part, due to the fault resistances being within the critical range. Consideration is now being given to the possibility of reducing the fault currents under phase-to-ground fault conditions by using transformers with delta connections on the 60-kv. side and possibly by removing the grounds from some of the transformer neutrals where more than one bank is located in a given station.

It was found by experience that very greatly improved operation of the 220-kv. system was obtained by reducing the time settings on the relays for the 60 kv. lines out of the Eagle Rock and Laguna Bell substations.

Governor Operation

In practically every case of a flashover to ground on the 220-kv. lines, the records obtained have shown that the governors on the Big Creek generators operate to increase the input to the machines. This effect, as shown by Figs. 10 and 11, is likely to produce instability. When a flashover occurs the capacity of the line for through power transmission is reduced, owing to the drop in voltage, and when the faulty section is finally cut out, the transmission capacity is reduced still further over that originally available. Also, the oscillations in phase position of the various synchronous machines require that a flow of power in excess of the average load on the machines be available to hold them in synchronism. Any increase in the average load will cause the peaks of the power oscillations to reach higher values, and if they then exceed the transmitting capacity of the system, the generators will pull out of step from the rest of the system. This point is illustrated by Fig. 22 showing how normal governor action may increase probability of pull-out, being the transient power limit of the system being represented by the line A. Curve B is a hypothetical curve showing the variation in power output of the sending generators, and Curve C is the prime mover input to them. It is assumed that the added power taken by the fault causes the system as a whole to slow down, thus making the governors of the waterwheels admit more water. The peaks of the power output oscillations increase until they reach the maximum capacity of the system at which point the momentum of the generators in their oscillation cannot be absorbed by the system and they pull out. When the machines overspeed, the governors finally operate to reduce the input as shown by the continuation of Curve C. The remedy for this condition is to have a system of control that will partially close the waterwheel gates upon the occurrence of a major disturbance, and later, after a proper interval of time, reopen them to their previous value.

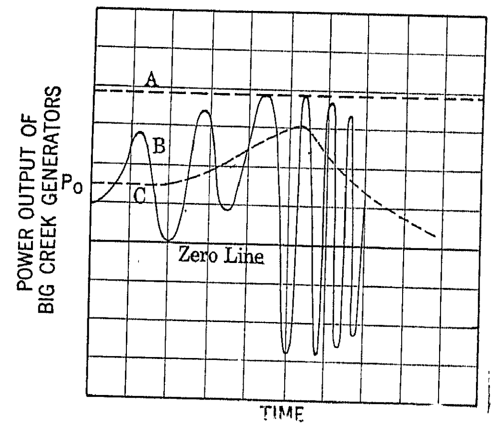

Fig. 22

The purpose of this arrangement would be to temporarily lower the input to the machines to conform to the temporarily reduced capacity of the transmission lines, and after the trouble is cleared, to gradually resume the normal load. Since at light loads it is unnecessary to take any special precautions to obtain stable operation, the relay-selecting scheme would be arranged to prevent operation unless the transmitted load was in excess of a certain predetermined value. This scheme is now being given consideration for use on the Big Creek generators. Depending upon the rate at which the gates can be closed, the use of a device of this kind should materially reduce the number of disturbances causing interruption of service, and, in the case of those which do, should facilitate the restoration of service by permitting the system to pull together more rapidly.

Regulation

In every case observed with the exception of that illustrated by Fig. 15, loss of synchronism, if it took place, did not occur until one second or more after the beginning of the disturbance. This shows that an appreciable time is available in which the field excitation of the synchronous machines may be increased to conform to the additional requirements. This can be accomplished only if the voltage regulator is capable of responding quickly and accurately and the exciters are able to build up in voltage rapidly. The object of a quick-response excitation system is to rapidly build up a voltage across the field winding of a synchronous machine, to provide sufficient additional magnetomotive force to neutralize the demagnetising action of the short-circuit current flowing in the armature windings. Owing to the fact that with a high resistance fault the voltage on one of the good phases may actually rise, the ordinary voltage regulator, if connected to this phase, would tend to reduce the excitation. This possibility can be overcome by the use of a regulator operated by means of a positive sequence network, and the new generators for power house No. 2-A, in addition to having a quick response system of excitation, will also have this type of regulator.

Transmitted Load

Whether or not a given system is able to withstand a disturbance is determined by the particular combination in which the controlling factors occur, as discussed in previous paragraphs. It is therefore impossible to place a definite numerical value on the transmission capacity of the system. However, data are available on a sufficient number of cases of flashover to permit of curves being drawn, showing the percentage of flashovers which cause outages at different loads. The curves of Fig. 8 were drawn for troubles originating on the 220-kv. system only, for the over-all operation of the system and for those cases in which perfect relay operation was secured. These curves show that the probability of an outage increases with the load being carried. The permissible operating loads depend largely upon local factors, such as frequency and time of occurrence of disturbances and perhaps even more upon how far it is justifiable to increase the cost of power in order to achieve greater reliability of service, etc. On the Edison system most of the flashovers occur in the early morning hours, when the transmitted load is low, (as shown in Fig. 7), thus making operation at high loads feasible in the daytime. In regions where lightning is responsible for most of the flashovers and the plant has storage capacity, the load may be reduced upon the approach of a storm to minimize possibility of an outage.

Conclusions

1. There are various standards of service which may be considered. Perfect continuity is not economically feasible; the next best thing is to so reduce the effects of short circuits as to allow only momentary disturbances thus causing but slight inconvenience to the consumer.

2. It has been brought out that one of the main factors in reducing disturbance and preventing loss of synchronism between the generating and receiving ends of a transmission system is the rapidity with which relays and switches can be made to isolate any trouble. It appears very probable that by a material reduction in the time now taken, troubles could be successfully cleared when transmitting much greater amounts of power than at present, and this same high standard of service could be maintained. Looking at this from another viewpoint, systems that might be furnishing but mediocre service would have that service vastly improved in quality by such change in switch operation, provided the transmitted load were not changed. On the other hand, unless it is possible to get extremely fast switch operation, less shock is produced when one end of a faulty section is cleared a short time after the other.

3. Quick response of generator field excitation to regulation aids in maintaining synchronism by preventing, so far as possible, a drop in generator field flux. The drop in generator terminal voltage will then be determined by the generator leakage reactance, being less with low values of reactance. Similarly, low transformer leakage reactance is beneficial.

4. It also appears that a device to decrease the output from the Big Creek generators immediately upon the occurrence of a short circuit will decrease the tendency to get out of step by reducing the transmitted load. Such a device might take the form of a relay operating upon the waterwheel governors. The greater part of the load so dropped would be picked up by generators at the receiving end, so that the net effect upon the system frequency would be inconsiderable.

5. One of the most important points brought out by the tests was the relation between the severity of the disturbance and the amount of ground current upon short circuit; this demonstrates the value of adopting means to limit short circuit currents. The higher the voltage of the system, the more pronounced is this effect.

6. The amount of power that can be transmitted consistently over any given line depends upon several factors including the standard of service required, the exposure and susceptibility to outside disturbance, and the probability of these disturbances occurring at a time when maximum loads are being carried. This is well illustrated on the Southern California Edison Company's system where, due to the nature of the chief cause of short circuits, they have occurred at off-peak periods resulting in a minimum of outages.

It may be suggested that under different conditions where causes of short circuits, such as lightning, might occur at any time, it would probably be advisable to take further precautions against outage unless conditions permit of a slightly lower standard of service.

7. All the records showed that synchronous condensers at the receiving end stayed in step with each other and their bus voltage; also all Big Creek generators would stay in step together so long as the generating and receiving ends of the line stayed in step.

8. Practically all short circuits have been single phase to ground and calculations for relay design and power limit should concentrate on this condition.

9. Short circuits on either 220-kv. or lower tension lines, close to terminal substations, will cause approximately equal disturbances to the 220-kv. system.

10. When a single-phase flashover occurs, there is an increase in total system load due to the power consumed in the fault. This additional load causes a transient redistribution of power between the different synchronous machines, which is largely determined by their kinetic energy and the electrical network, causing them to shift in phase position and thus set up power oscillations or surges. The magnitude of these surges depends upon a number of factors, such as the location and resistance of fault, transmitted load, etc. The ability of the system to absorb these oscillations without loss of synchronism depends upon the electrical rigidity with which the various machines are tied together, permitting a sufficiently high synchronizing power to be developed. The amplitude of these power surges will be reduced by anything that decreases the power consumed by the short circuit. Synchronizing power will be increased by decreasing the reactance of generators and transformers and by reducing the amount of line cut out to isolate the trouble.

Discussion

Svend Barfoed: The records obtained on this system show that disturbances originate on the transmission line, and that there are only two unknown causes of flashovers in the entire period. This is a fine performance of watchfulness.

The design of transmission lines is still undergoing evolution, and better performing lines as regards flashovers can certainly be expected. It would pay to give reconsideration to the structural design and construction of transmission lines, giving regard simultaneously to mechanical and electrical features.

These latter should not be viewed separately by different departments of an organization. By reconsideration of the whole problem, the cost of construction may be greatly reduced and improved electrical characteristics obtained. This is mentioned, because it would not be justified to assume transmission line design and construction as standardized. It is certainly not possible to have perfect continuity of service, but it should be possible to approach that condition at no increased cost of design and construction.

With regard to synchronous machines it will be advisable to proceed with caution to reduce the reactance to secure increased power transmission limit. It is suggested that the degree of stability of machines between themselves for use in the same station be investigated on the test floor without line or transformers.

There also may be investigated how a machine with vanishing reactance behaves on short circuits.

Roy Wilkins: This paper gives for the first time definite operating data on a specific 220-kv. line.

The operating problems on the two 220-kv. lines in California are much the same. The method of attack has been somewhat different, however, due primarily to different initial system set-ups.

The Pacific Gas & Electric Company lines, (202 mi. long), are 60-cycle, with somewhat more insulation than those discussed in the paper for the above reasons (*i. e.*, original set-up).

On the Pacific Gas & Electric Company system there has been an average of four flashovers per 100 mi. of circuit per year. Of these, the greater portion, where the trouble can be definitely located, are caused by lightning and birds.

The usual flashover is relayed out and the line is put back in service as soon as the switching can be done. Some 30 or 40 per cent of the troubles can never be located.

In those comparatively rare cases of mechanical failure the line remains out until repaired. In all ordinary flashovers no repairs are needed. During the past two years two cases have occurred when both lines were out at once. In one of these one line went out due to trouble by lightning, and while it was being cut in, the second relayed out from the same cause. Both were switched in immediately and remained.

In the second case both relayed simultaneously and were switched in without further disturbance. The Pacific Gas & Electric Company lines are comparatively lightly loaded,—from 120,000 to 150,000 kw. for both lines. Their performance lies, therefore, below that part of the curve marked *C* on Fig. 7 of the paper, and a minimum of trouble due to instability is to be expected. We have, however, enough of operating data to give a very definite idea as to the relay and switching requirements:

1. It has been demonstrated that a section of line in trouble should best be cleared in the shortest possible time.
2. It is desirable to protect each line independently so that it has normal protection under all conditions.
3. Protection from phase to ground is by far the most essential, and should be set as low and as fast as possible.
4. All 220-kv. systems now in service are grounded Y-connected on the high-voltage lines so that ground protection can be satisfactorily accomplished only on the high-voltage side.
5. Low ground resistance (such as is caused by multiple grounds from ground wires grounded at every tower) will cause much greater current and therefore greater disturbance than relatively high ground resistance.
6. There is room for a vast improvement in circuit-breaker operating time, since in those relay systems where satisfactory ground relaying is secured, the greater portion of the total time is used in the oil circuit breakers, leaving very little for any differential in the relays.

The particular ground relay scheme used on the Pacific Gas & Electric Company lines has been in use on the lower voltages for about seven years with entire satisfaction; in fact, it is the only line protection which has been tried that was satisfactory.

Most of the above points have been checked independently against the data given in the paper, and they are wholly in accord with the conclusions there given. These conclusions are very worth while studying by any one at all interested in 220-kv. transmission, for on their proper use depends the success or failure of 220-kv. transmission.

F. R. George: I might add our experience in connection with 220-kv. lines operated by the Pacific Gas & Electric Company. Mr. Wood mentions 65 interruptions in 18 months. Covering that same period of time in the operation of Pacific Gas & Electric Company lines there was a total of 18 interruptions. In the entire period of time during which the 220-kv. system has been operating, Mr. Wood mentions 96 interruptions and we found less than 40 interruptions. These figures give an idea of the reliability of systems operated at high voltages.

As stated previously, it must be borne in mind that the system of the Pacific Gas & Electric Company is not fully loaded and the question of stability does not enter into the problem as actively as it does in the case of the Southern California Edison Company.

Harold Michener: The really assuring and hopeful aspect of the paper is that the authors seem to have discovered some of the reasons for the satisfactory operation of the system under the increasing demands that have been placed upon it and some of the things that can be done to make the operation still more successful under still heavier load conditions. Most of the improvements suggested can be applied either to additions to the system as they are made or to existing parts of the system,—the latter involving the greater expense.

Probably the most important improvement, the very much quicker isolation of the section of line in trouble, does not seem to be immediately available. Concentrated effort should be directed toward the shortening of relay and switch operation.

The findings and the thoughts expressed on the effect of high resistance in the fault-to-ground circuit are particularly interesting. It was not long ago that we were giving serious consideration to the best way to get a low-resistance ground connection at the foot of the towers, in order to meet the conditions of maximum overhead ground-wire protection, and to make the potential gradient from the tower members to the surrounding ground as low as possible.

Now we learn that the natural high resistance from tower to ground has been a saving feature in our transmission-line operation. This is fortunate, for in general in our territory it is easier to get a high-resistance connection between tower and ground, but, of course, precautions must be taken to avoid unreasonably high potential gradients at these points, although no group of men has agreed on a definition for "reasonableness" in this connection.

By several compromises a condition of most satisfactory operation may be obtained. These compromises will be between high resistance and low potential gradient at the tower footings, between high resistance in the ground connections at transformer neutrals and low voltage to ground from the transformer windings, and between high-resistance and low-resistance overhead ground wires.

We are in a fair way to get further information upon the effect of a low-resistance fault-to-ground circuit, although, of course, we hope the faults will not occur.

The 220-kv. lines are being extended from Laguna Bell substation to Lighthipe substation, a distance of 6½ mi., and from there to the Long Beach steam plant, a distance of 10 mi. Under the present plan the neutrals of all the transformer banks at these stations will be grounded without appreciable resistance and the ground connections at the tower footings will be of low resistance, special care having been taken to have a 4/0 copper cable attached the full length of one of the piles in each footing where piles were used and to have two standard copperweld ground rods driven in the bottom of the hole for each grillage footing. The soil conditions throughout are such that low-resistance ground connections should be expected. This means of getting low-resistance connections between tower footings and ground was installed because the lines are in a highly developed territory, and it was felt that the potential gradients between tower footings and ground, in case of an arc to the tower, should be kept to a minimum.

One ½-in. steel ground wire will be installed on each of the two single-circuit lines from Laguna Bell to Lighthipe, and one 4/0 copper ground wire will be installed on the double-circuit line from Lighthipe to Long Beach.

The work on power-system stability being done jointly by the manufacturers and the power companies is yielding very beneficial results and should be continued. In this way the whole industry learns to talk the same language.

P. B. Garrett: When we first installed the test equipments we used a type "MC" quick-acting relay for initiating purposes. As noted in the paper, this relay was energized from a current transformer in the grounded neutral connection. We did not expect that this relay would be caused to operate on switching operations. We did find, however, that our equipment was picking up on switch operations, due to the ground current incident to non-simultaneous operation of the three legs of the circuit breakers, which results in a momentary unbalanced condition.

To overcome these undesirable operations, we resorted to the type "CO" low-energy overload relay, set for a very short time delay, for initiation purposes. The time lag was not particularly harmful, because even with this time delay, the film is usually well under way and the record started before the important power swings occur.

One point came up in connection with the installation of the oscillograph equipment at Vestal Substation. Due to the fact that the cold resistance of the lamp filament is but one-fifteenth its hot resistance, the lamp takes a large rush of current when first energized. The lamp transformer which was supplied as a part of the oscillograph, did not have sufficient capacity to hold up the potential at the start, and the drop in applied voltage greatly increased the comparative time taken to bring the lamp to full brilliancy. By means of a special transformer of ample capacity the time lag was greatly decreased. Previously, the motor would move the film a considerable distance before the record was started.

One point might be of interest in connection with the compilation of records pertaining to flashovers. We found it necessary or very desirable to make a special form for each of the stations, this form to be filled in by the operator at the time of the disturbance; thus we are certain of obtaining complete data relative to the operating conditions at that station at the time of the system trouble. We also made a special form for use in the main office for filling in general system data, such as the system set-up, total connected kv-a., and the like.

E. R. Stauffacher: I should like to call attention to Fig. 1 showing the system connections on the 220-kv. system. Between Big Creek No. 3 and Vestal, 45 mi. north of Vestal, there is a new station known as Rector which is now in operation, and which is tapped across the two lines.

There will also be another line from Gould to Magunden and Magunden to Big Creek No. 3, known as the Vincent line and two lines from Laguna Bell, to a new substation known as Lighthipe and from Lighthipe to the Long Beach Steam-Plant No. 3.

The application of relay protective devices to this changed 220-kv. system, owing to the taps and combination of parallels and taps, has been quite a problem, and it is my hope some day it will be more of a clear-cut proposition, so there will be no need of as many as six or seven switches operating to clear a short circuit.

In Table II, "Causes of Flashover," information is compiled which should be of considerable interest to anyone who is contemplating a 220-kv. system, if conditions are anywhere near comparable. With only one or two exceptions the troubles have resulted in line-to-ground faults.

One thing I should like to mention particularly is the speed with which the troubles are located by the transmission department. Very rarely does it require over half a day to locate the trouble and diagnose the cause. This is certainly helpful when analyzing the operations of the protective relays and the flow of ground current at the time of the flashover.

In Table III under the heading "Total Ground Amperes," a tabulation is made, which might be interesting not only to other central-station engineers, but also to telephone engineers. I know they are quite concerned with the amount of ground current which occurs at the time of flashover. Probably by analyzing these current values, knowing what the trouble was and its location, the amperes in the ground may not prove to be as destructive as might at first be supposed. However, the conditions regarding parallels and length of exposure of course determine how much damage might result.

In addition to trouble on the 220-kv. line, the troubles on the

66-kv. line, are also of considerable concern, particularly near the major receiving stations. Due to the necessity of time-cascading with relays, the longest time on the relay settings is at the location where the heaviest 66-kv. short circuits will occur, and in the interest of system stability it is necessary to cut down the time as much as possible, even at the expense of selectivity as to relay operations in some cases.

Regarding the stability of a system it seems to me that there are four outstanding requirements for maintaining stability at the time of a severe short circuit.

First: High speed of relay operation.

Second: High speed of switch operation—and by high speed, I am not talking in fractions of a second but mean one or two cycles. This is not possible now but I hope it will be a reality in a few years.

Third: Design of the generators—particularly as regards its short-circuit-ratio characteristics.

Fourth: The application of quick-response excitation to the generating equipment.

F. M. Gillespie: (communicated after adjournment) It is interesting to note the high values of kilowatts (energy) consumed by phase-to-ground faults on the 220-kv. system. The writer has been severely criticized at times for even hinting that line faults could be of sufficiently high power factor to consume any appreciable amount of energy; he has heard arguments tending to prove that load is always lost as soon as short circuits occur and has been told that operators and recording instruments must be in error for indication of speed drop instead of speed rise at times of line trouble.

The particular system to which I will refer carries a hydroplant peak of about 160,000 kw., has in service close to 1400 kilometers of 80-kv. and 110-kv. circuit and over 2000 kilometers of 22-kv. and 25-kv. overhead distribution circuits. In the early days of our operation we experienced considerable trouble with hunting of the generators when high-voltage trouble occurred; after restricting the rate of opening of turbine-gate-operating servomotors conditions were so stabilized that it is only on very rare occasions that there is any visible tendency for machines to pull out of step.

In our case the retarding of gate-opening time was accomplished by insertion of suitable diaphragms in pressure-oil pipes supplying the opening end of the servomotors. At least one American turbine builder accomplishes the same result (prevents opening of turbine gates on momentary overloads) by means of an adjustable collar on the spindle of the governor head. Our first adjustment was to increase the gate-opening time for full travel to 20 sec., and after further growth of the system this was altered to 30 sec. It is found that normal load fluctuations do not cause objectionable speed variations (we carry a certain amount of suburban railway load), and the rise in speed accruing to loss of load caused by voltage dip during period of faults is considerably less than it was when the governors were adjusted to open the gates in 3 to 6 sec. for the full stroke of the servomotors.

Phase-to-phase short circuits on high-voltage lines are, in proportion to the number of phase-to-ground faults, of very rare occurrence, but sufficient of these have taken place to prove that they can also consume sufficient energy to cause frequency drop, especially if some distance away from generating stations. On our 25-kv. network faults, irrespective of whether phase-to-ground or phase-to-phase, cause increase of load at generating stations. In fact our miniature system for calculating relay settings has had to be so arranged that impedances are shown instead of simply reactances, to allow sufficient accuracy. This should be sufficient to indicate that there is enough resistance in high-voltage networks to represent considerable energy consumption under short-circuit conditions.

The experience with the 220-kv. system as described, and experience on other systems of lesser voltages leads one to question the desirability of graded insulation on high-voltage windings of transformers with the attendant solid grounding of one end of each leg to the tank, as this eliminates the possibility of inserting grounding resistance between transformer star points and earth. There seems to be no doubt that on large systems a certain amount of neutral resistance is often desirable and offers a more reliable means of controlling the dimensions of short-circuit current and energy consumption than variation of the number of transformer neutrals connected to ground. The use of a fairly high value of grounding resistance would seem to allow securing a more constant value of ground-fault current than the use of a high-resistance ground wire as with the latter the variation in value of resistance of return circuit according to the location of the fault may cause the fault current to vary over a very wide range.

I should like to inquire if the authors of the paper can trace any cases of hunting or loss of synchronism to different systems of excitation. That is, is there any special tendency for stations with individual direct-connected exciters to pull apart from stations with central excitation such as a water-wheel driven exciter set or motor-generator exciters fed by a house generator, the exciter speed and voltage in these cases being independent of the main generator speed.

R. J. C. Wood and L. F. Hunt: Mr. Barfoed mentions an investigation of the relative stability of machines in the same station. We did not find there was any trouble on that account. He seemed to think there might be some difficulties due to reducing the reactance.

I cannot see that that would cause the machines to fall out of step among themselves, but would rather tend to keep them together.

The showing of the Pacific Gas & Electric Company's 220-kv. system is extremely encouraging to any one who contemplates building a 220-kv. line.

Mr. Michener's remarks regarding the compromise which has to be made between (a), low-resistance grounds with a view to decreasing the potential gradient in the ground around a tower footing when a flashover occurs and (b), the apparent desirability of having a high resistance there for stability purposes, is just one more illustration that you cannot get everything out of the "Standard Handbook."

It is not quite clear whether Mr. F. R. George in his discussion refers to interruptions where load is lost, or to flashovers irrespective of whether load is lost or not.

The 65 interruptions referred to by him were 65 flashovers during 18 months; of these only 11 caused interruption to service. Of the 96 flahovers experienced during the whole time of operation, 30 actually caused interruptions; 20 of these 30 occurred when relays were out of service on account of construction and repair work. Judging from Fig. 8 as to what would have happened had the relays been in service and taking into account the load being transmitted at the time, proper relay operation would have resulted 14 times, so that the net result would have been 16 interruptions over a period of 40 months.

It is entirely probable that the 40 cases of trouble occurring on the Pacific Gas and Electric Company's line were flashovers and not all caused interruptions. It was felt only fair to emphasize the distinction between flashover and interruption as otherwise a wrong impression of the reliability of 220-kv. systems might be obtained.

We have no definite information upon the question raised by Mr. F. M. Gillespie and cannot state whether direct-connected exciter systems tend toward lessened synchronizing power to any practical extent.

S. B. Griscom: It is very reassuring to note from the discussions of Messrs. Wilkins and Gillespie that their independent experiences on other systems have lead to conclusions substantially in accord with those expressed in the paper. Mr. Gillespie's reference to the power factor of short circuits is

particularly interesting in this regard. Despite visual evidence of frequency drop during short circuits it has apparently been difficult for him to establish the fact that short circuits, including those from phase to phase on low-tension lines may cause considerable momentary overloads. It is for the purpose of obtaining data for firmly establishing general working principles on a given system that the application of high-speed automatic recording apparatus to power systems has been advocated.

Mr. Michener's comments on fault-to-ground resistances show the number of considerations involved in determining upon the method of grounding to be employed at stations and towers for the Southern California Edison Company. The considerations are worthy of study before fixing standards of grounding procedure, since as he points out, different parts of the system may be operated under different conditions.

Mr. Stauffacher's point in regard to simplification of 220-kv. line connections is very well taken. The true measure of transmission-line cost is the cost per mile per kilowatt of permissible load transmitted. Arrangements which do not permit satisfactory line relaying or switching must necessarily reduce the permissible load that can be handled by the circuits thus increasing the cost. For this reason, a connection scheme which involves more apparatus or lines, while costing more in actual dollars, may actually cost less per kilowatt of permissible load.

Mr. Stauffacher has mentioned the application of generators of high short-circuit ratio. The stability characteristics of generators and condensers during transients is largely determined by the leakage or transient reactance of the machine, provided the field flux is maintained substantially constant. This may be accomplished by suitable combinations of machine short-circuit ratio and excitation-system response.

With reference to Mr. Gillespie's question on different systems or excitation, there have been no cases within the authors' knowledge where stations with direct-connected exciters have pulled apart from stations excited from sources independent of the main generators. In general this would not be expected since a regulator is capable of changing the exciter field flux at a faster rate than the speed is changing.

Equipment for 220-Kv. Systems

BY J. P. JOLLYMAN[1]

Member, A. I. E. E.

Synopsis.—*This paper discusses the characteristics of equipment which have been found most suitable for use on 220-kv. systems or on extensive lower voltage systems. Consideration is given to general system design, governors of prime movers, generators, excitation systems, transformers, high-voltage oil circuit breakers, transmission line, and the equipment of substations.*

The result of four years' operation of a 220-kv. system have proven it to be as reliable as a 110-kv. system. The economies of 220-kv. transmission have been realized.

* * * * *

EXPERIENCE gained from the operation of a pioneer project confirms the wisdom of the original choice of equipment or shows where improvements can be made. This paper will discuss briefly the characteristics of equipment found most suitable for a 220-kv. system in the light of four years of operation. While the statements apply particularly to 220-kv. 60-cycle systems with long lines, they also apply to lower voltage systems if due allowance is made for the differences in magnitude.

The 220-kv. transmission systems are required for three principal purposes: (1) for long distances and considerable power; (2) for short distances with large amounts of power; and (3) as a part of an ultimate network. The requirements of equipment for the three types of systems are essentially the same. The systems having long transmission lines are the most difficult to operate on account of the very large charging kv-as. that must be supplied. The system with large power but with short transmission is less difficult to operate but imposes very severe duty on the oil circuit breakers.

General System Design

When planning a transmission system for 220-kv. operation, the entire system with its connected equipment must be considered as a whole or as a part of the whole of the ultimate system. The sections of transmission circuits which must be handled as a unit have to be determined, since the kv-a. required to bring these sections of transmission to normal voltage decides the size of generating units and of synchronous condenser units.

Experience has very definitely established the necessity for operating 220-kv. transmissions as well as lower-voltage transmissions containing a considerable amount of transmission mileage with the transformer neutrals solidly grounded not only at the generating stations but also at all substations. All transformer banks should be equipped with delta-connected windings for the purpose of stabilizing the relation between the separate phases as well as improving relay operation. In the case of transformers at generating stations, the delta winding becomes the low-voltage winding of the transformer bank. In the case of transformers at substations, the delta windings can frequently be used to supply the necessary synchronous condensers.

Due consideration must be given to the supply of charging current, and this supply must take into account the fact that the generators, when carrying load, must operate at a high power factor if stability is to be maintained. These requirements will generally make it necessary to operate a high-voltage transmission with a drop in voltage in the direction of the flow of power. The effect of this operation will be to necessitate supply of charging current from the receiving end of the line, leaving the generators free to operate at a high power factor.

Under heavy loads, it is possible to supply sufficient boost at the receiving end of the transmission section to bring its voltage to an equality with the sending end of the same section without causing a leading current in the generators at the sending end. In very extensive networks where the flow of power may be reversed, operation at the same voltage at all points may become necessary.

Should this be essential, definite provision for a supply of charging current at some of the generating stations will have to be made.

Some flashovers of line insulators seem inevitable. Interference from external sources cannot always be avoided, nor has any insulation yet been found which will withstand the effects of all kinds of lightning. When a failure does occur, the section of line involved in the failure must be disconnected from the system with the least possible delay. While the arc resulting from a flashover may be extinguished by dropping the system voltage, this operation will nearly always result in the loss of synchronism between the generating stations and the load. It therefore seems better to cut out the section of line on which trouble has occurred.

Experience shows that this can be done in the majority of cases without loss of load, provided the sections of line remaining in service have sufficient capacity to carry the total load. To disconnect a section of line on which trouble has occurred requires the use of automatic relays. Excellent satisfaction has been experienced with the use of directional overload and directional residual relays. It is possible to connect the directional residual relays to the system in such a manner as to secure inverse time operation. With

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such a system of connections, it has been found possible to relay out one of two parallel lines even though the trouble was within one per cent of the total distance from one end of the section. To attain this result from the balanced system of relays is extremely difficult, if not impossible.

Generating Stations

The prime movers of generators employed on high-voltage systems will usually be steam turbines or water-wheels of the reaction or impulse type. The only special requirement of prime movers for such systems is that their governors should hold the speed very close to normal without hunting at no-load. This requirement must be met if quick operating is to be attained.

In the case of certain types of hydroelectric plants where pulsations in penstock pressures tend to cause the waterwheels to hunt when running at no-load, this is not an easy requirement to meet. The use of a load limiting device on the governors which will permit a convenient adjustment of the output of the prime movers has been found very useful. Especially in hydroelectric plants it is frequently desirable to limit the output of many of the units and permit only a few units to govern. The load limit device permits of such operation in the most advantageous manner.

The generating units may be called upon to build up the voltage on transmission line sections for the purpose of tests or for the purpose of bringing up a section to put it in service. In either event the generator must be first connected to the line with little or no field current. The fact that no terminal voltage, or a very low terminal voltage, would exist on the generator prior to the time the line is brought to full voltage prohibits the use of electric drive governors. The later types of mechanical drive for governors have proved so satisfactory that there seems little reason to desire the electric form of drive.

From the standpoint of the function which they must serve in connection with the operation of this system, generating units connected to high-voltage systems fall into two classes: (1) Tho seunits which must be of sufficient capacity to handle designated sections of the transmission lines (such units will generally be of fairly large size); and (2) smaller units having insufficient capacity to handle any part of the high-voltage system whose function is merely to feed in a certain amount of power but which must be cleared from the system in case of trouble or in case of line test.

The larger or control units should have fairly high short circuit ratios so that they may have good stability during system disturbances and be able to carry charging kv-a. at least equal to rated capacity without exceeding rated terminal voltage. Such generators should also stand occasional overvoltages of the order of 50 per cent since switching operations may occur at any time which will result in high over-voltage.

A smaller generator should have a sufficiently high short-circuit ratio for stable operation and should have the ability to operate with considerable overvoltage at least for brief periods.

Excitation Systems

Excitation systems for generators supplying high-voltage lines must be automatic as to their voltage control and must operate with the highest practicable speed, especially in a case where direct-connected exciters are used. If this is not done, the generator voltage will vary far too much with the changes in power factor resultant from the changes that occur, especially in case of line trouble. The automatic voltage regulators should be direct-connected to the generators and not to the station bus. The generators are thus protected from protracted overvoltage in the event of their being tripped off the bus.

The use of direct-connected exciters, which is desirable from nearly every standpoint, presents an additional problem because of their being affected by generator speed. Hence, on such an increase of generator speed as will be occasioned by sudden loss of load, the terminal voltage of the generator tends to increase with the square of the increase of speed. To avoid this compounding effect, the automatic control of the excitation system must have a very quick response.

Sudden loss of full load, with large hydroelectric units driven by reaction turbines, results in a speed increase of the order of 30 per cent. In the case of impulse wheels, this speed increase can be reduced somewhat provided governor action in less than two sec. is permissible. With excitation systems having fairly high speed response, it has been found possible to hold the generator terminal voltage to a rise which is not greater than the per cent rise in speed.

In order that each main generating unit may be as independent as possible, the use of direct-connected exciters, with a voltage regulator for each unit, has been found very satisfactory.

Transformers

Modern high-voltage transformers have given very good service in high-voltage systems. The reactance of these transformers should be kept as low as can be reasonably obtained. If this is not done, the transformers will contribute to bad voltage regulation of the system especially when lines are being tested or sections of lines placed in service.

The short-circuit current through transformers connected to long distance hydroelectric systems tends to be limited by the generating capacity or the line impedance rather than by transformer impedance. It does not seem necessary to introduce any additional reactance in the transformers for such systems to protect them from damage from short circuits.

In the case of transformers fed from large steam turbine generating units, great care must be exercised to provide for their safety under a short circuit on account of the higher momentary short-circuit currents of steam turbine units as compared with water-wheel

units. Like the generators, the transformers must stand considerable overvoltage. However, as transformers designed for an induced potential test of 2.73 times normal voltage have given perfect results on solidly grounded neutral systems, it does not appear necessary that for such systems they should be designed to stand a higher test voltage.

For generating station transformers with low voltages of 11 kv. or 13 kv., the core-type transformer has much to commend it from the standpoint of the simple form of major insulation. For auto-transformers or for transformers having high low-tension voltages the shell type of design permits of a better control of the characteristics of the transformers.

High-Voltage Oil Circuit Breakers

To lessen the effects of short circuit or grounds on high-voltage system and to reduce the amount of energy which must be dissipated within a high-voltage oil circuit breaker, such circuit breakers should operate with very high speed. The total time of operation for an opening stroke should be well under one-half second. Any longer time than this may result in serious effects in the transmission network.

Admittedly, this requirement is a difficult one to meet. However, it is agreed that the problem of attaining still higher operating speeds in large circuit breakers is one of the most important confronting the transmission industry. In times of peace, some of the mechanical skill which has been applied to the design of instruments of warfare could very profitably be devoted to the refinement of the mechanical design of oil circuit breakers.

An incidental requirement for the satisfactory operation of an oil circuit breaker is that it must be mechanically trip free. This trip-free function must be so arranged that a minimum time is consumed between the instant that a short circuit is encountered and the instant that the circuit breaker will be opened.

With the establishment of 220-kv. systems with considerable lengths of line, leading currents of some magnitude are made available and it has been found that the rupture of such currents creates lengths of arcs within oil circuit breakers very much greater per ampere of leading current than per ampere of short-circuit current of a lagging power factor. In fact, the length of arc drawn within oil circuit breakers is of the same order of magnitude for the charging current of a 200-mi. section of 220-kv. line as for a short circuit close to the oil circuit breaker.

Transmission Line

The transmission line as a mechanical structure has given excellent service. Reasonable factors of safety were employed on the structures, the design of which is subjected to test to destruction. Low stringing tensions were employed for the conductors, primarily for economy in cost of the towers. No trouble has been encountered from conductor vibration. It is felt that the low stringing tensions contribute to this desirable result.

No difficulty or evidence of undue depreciation has been encountered in the insulators used. The mechanical loads imposed on the insulators are rather moderate. With a material of the character of porcelain, it seems wise to proceed with caution in regard to the loading imposed. While high strengths have been developed for test load conditions in comparatively small porcelain suspension insulators, it is felt that the best way to employ this strength is to increase the factor of safety rather than to increase the initial load on such units.

In the case of the system with which the writer is familiar, accumulated evidence appears to point very directly toward the benefits to be derived from the use of an amount of line insulation which gives high flashover values. In the case of 110-kv. lines it is definitely known that even a comparatively small increase in the length of insulator strings secures a marked reduction in the number of the cases of flashovers experienced. There seems no reason to doubt that the same will be true in higher-voltage systems. This statement is made for a territory where lightning is a comparatively minor factor. In territory where lightning is a frequent source of trouble, caution should be used to see that the flashover value of the line insulation is not so high as to cause failures in the insulation of switches of transformers. However, if there is any question of the ability of the apparatus to stand the flashover voltages developed by the line insulation, it would be better to increase the breakdown values of the apparatus insulation rather than to decrease the flashover values of the line insulation.

One of the most trying problems, and one concerning which there is no certain solution in sight, is the question of maintaining sufficient insulation in sections where conditions permit of excessive surface leakage of line insulators. This problem is particularly acute in California in districts close to the ocean where the combination of the westerly trade winds and the ocean fogs results in a rapid accumulation of dirt on the insulator surfaces which are frequently wet by the fogs. The only method thus far discovered for securing high continuity of service in these sections is by artificial cleaning of the insulators during the months in which rain does not fall.

Some device for suppressing corona discharge of the conductor and wire clamps at the insulators appears highly desirable, since such a device tends to offset the distortion of electrostatic field at the points of support. It is not so certain that devices are required to improve the grading of the voltage impressed on the several units of long suspension strings. Apparently, as good results have been obtained in operation with devices for suppressing corona that have little or no grading effect as have been obtained with devices for suppressing corona that are arranged for considerable grading effect.

An insulator string is most likely to fail when wet by

a fog. At this time the distribution of voltage is undoubtedly determined by leakage currents rather than by the condenser effect of the unit. Obviously, grading devices are ineffective at the very time an insulator string is most likely to fail.

It is believed that the conductors of high-voltage circuits should be transposed so that the electrical characteristics of each phase wire may be as nearly like the characteristics of the other phase wires as possible. Additional reasons for transposing each circuit occur where two parallel circuits are used. In this case, transpositions should be so arranged that one circuit is transposed with respect to the other. In this way, inductive effects of trouble on one circuit upon the other circult are minimized.

The use of double-circuit towers appears to be permissible where no sleet is encountered. This construction is a very distinct economy compared with the use of two separate single-circuit lines.

Substations

The requirements of equipment for substations are similar to those of generating stations in practically all respects. The main transformers may be auto-transformers if the ratio of voltage transformation is not more than 2:1. In such transformers, delta-connected windings should be employed and may be used for synchronous operation if desired.

Synchronous condensers must work over the complete range from full boost to as much buck as they are designed to supply. Some economy of cost can be had if the bucking capacity of the synchronous condensers is not more than 60 per cent of their boosting capacity.

Where very long sections of transmission line must be handled, it will be found necessary to employ a synchronous condenser in addition to a large generator in order to supply the charging kv-a. for bringing the circuit up to full voltage. For this operation, the condenser may be attached to the circuit with little or no field excitation and the generator may be used to secure the desired voltage.

In certain substations, control being a number of outgoing circuits which it would be desirable to test by building up rather than by cutting into the bus, the use of a driving motor on a synchronous condenser, permitting the operation of the condenser as a generating unit, will be found very convenient. At first thought it seems best to make these driving motors of the induction type. However, it is believed that a synchronous drive motor will serve the purpose equally well and will have the advantage of operating with a greater air-gap. The synchronous driving motor should have the same speed as the synchronous condenser. The unit should be started in the usual way, using the main condenser.

When the main condenser has reached synchronism, the driving motor can be cut in to carry the unit while the main condenser is being used as a generator for test purposes.

A flexible switching scheme should be used for main substations so that the various operations may be conducted with the utmost dispatch. The arrangement should be such that access to any oil switch may be had without material loss of switching flexibility because oil switches require considerable maintenance.

In closing, it may be said that four years of operation have proved that a 220-kv. system can be expected to give as good service as can be had from a 110-kv. system. With four times the kilowatt capacity at approximately twice the cost per mile the 220-kv. system affords a very distinct economy in the cost of transmission where the amount of power is sufficient to justify the use of the higher voltage.

The success that has attended the operation of the pioneer 220-kv. systems proves that the economies of these systems can be realized and can be applied to increasing the transmission radius at a given cost or for decreasing the cost for a shorter radius.

Discussion

Harold Michener: Mr. Jollyman speaks of the dirt and the salt accumulation on insulators. Our experiences indicate that the only way to maintain satisfactory service is to clean the insulators as frequently as necessary, that frequency being determined by a study of local conditions.

R. J. C. Wood: An insulator string is most likely to fail when wet by a fog. At this time the distribution of voltage is undoubtedly determined by leakage currents rather than by the condenser effect of the unit.

That, I believe, is entirely true where there is not much lightning trouble; but the effect of grading a string is to increase the lightning flashover value.

This grading should be more valuable to those building lines in the East and mountainous parts, where lightning is more frequent than it is here.

Static Stability Limits and the Intermediate Condenser Station

BY C. F. WAGNER*
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and

R. D. EVANS*
Member, A. I. E. E.

THE development in power transmission has been in the direction of delivering increased amounts of power per circuit over greater distances. This trend raises two fundamentally important questions:

1. What constitute the output limitations of the alternating current system of power transmission, and
2. How close to these limits is it feasible to operate transmission systems?

During the past few years, investigations have been under way to find the answers to these questions. Stability has been recognized as the outstanding output limitation of power systems utilizing synchronous machines of the types now in use. There have been a number of proposals for increasing the stability limits of power systems. The use of lower system frequency and the reduction of the series impedance of the system are obviously of value in increasing the stability limits. Recently, the latter method, by decreasing the machine impedance, has been adopted in a number of transmission undertakings. Of course, raising the transmission voltage has been considered, but it is relatively expensive and does not avoid the "distance limitation" in lines approaching the quarter wave resonant length. This effect becomes important for distances considerably below the theoretical value because of the impedance of terminal equipment.

One proposal of greater promise than any of those mentioned in the previous paragraph is the use of the intermediate synchronous condenser station. In 1921 Mr. F. G. Baum† presented an important paper devoting a considerable part of it to the use of intermediate condenser stations, which he advocated as a method of making technically feasible the transmission of 60-cycle power to substantially unlimited distances.

Since the early proposals to utilize the intermediate condenser station to increase the stability limits of transmission systems, the entire subject has received a very great deal of attention before the Institute and in the technical press. During 1924, Messrs. Evans and Bergvall‡ presented the results of tests made during the previous year, giving experimental verification of the increases in stability limits possible by the intermediate condenser. The tests were made on a miniature power system and showed improvements as great as 42 per cent. In the bibliography is listed a number of technical papers published in America dealing with the intermediate condenser station problem.

*Both of Westinghouse Electric & Mfg. Co., East Pittsburgh, Pa.
†Bibliography, Item 1.
‡Bibliography, Item 3.

Presented at the Pacific Coast Convention of the A. I. E. E., Del Monte, Calif., September 13-16, 1927.

The best physical explanation of the elements entering into the stability problem in general and the intermediate condenser station problem in particular is obtained from a study of the mechanical analogy suggested by Mr. S. B. Griscom*. The mechanical model was first built by Mr. C. F. Wagner and used by him for the demonstration of the stability phenomena during the year 1926. In reality, the model is a synchronous mechanical transmission system used to simulate the action of a synchronous electrical transmission system.

The mechanical model as applied to a simple system

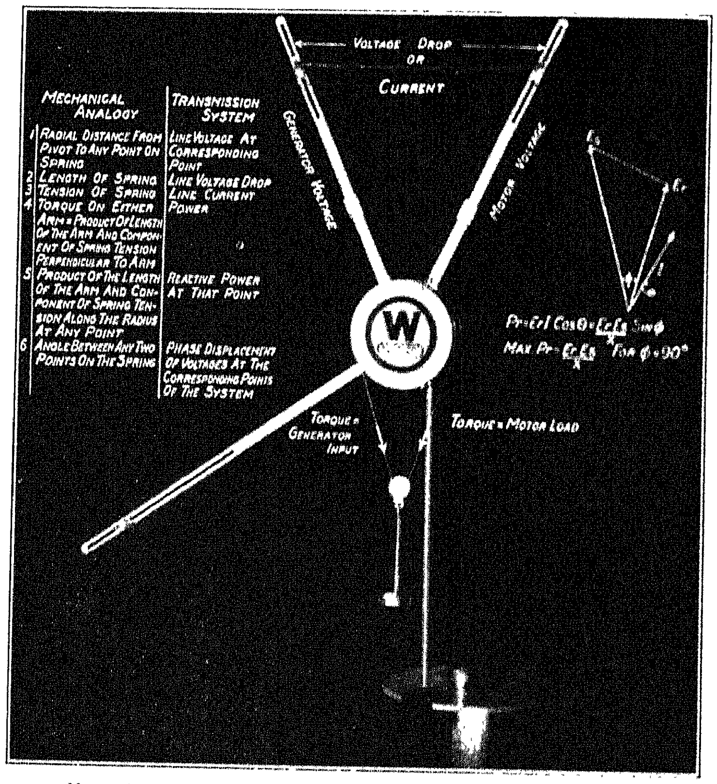

FIG. 1 MECHANICAL MODEL FOR TWO MACHINES

involving a generator, reactance line, and synchronous motor is illustrated in Fig. 1. The model consists essentially of two rotatable members mounted on a common shaft. Each member consists of a small flywheel to which a lever arm is attached. Each member is provided with cords so arranged that downward forces tend to rotate the members in opposite directions tending to separate the lever arms, this action being opposed by a spring connecting them. The points in the analogy are indicated by the table accompanying Fig. 1.

*Bibliography, Item 10.

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Such a mechanical system represents quite faithfully from the standpoint of stability all the essential phenomena that take place on a simple electric power transmission system. When the load is in excess of that required to produce a displacement of 90 deg. between the two lever arms under steady load conditions, the system pulls out of step, simulating the pull-out of an electrical system. Incidentally, it may be mentioned that when the resistance in the electrical system is neglected the pull-out takes place at the same angle on the two systems.

The power limits of the mechanical system can be increased by using a stronger spring, which corresponds

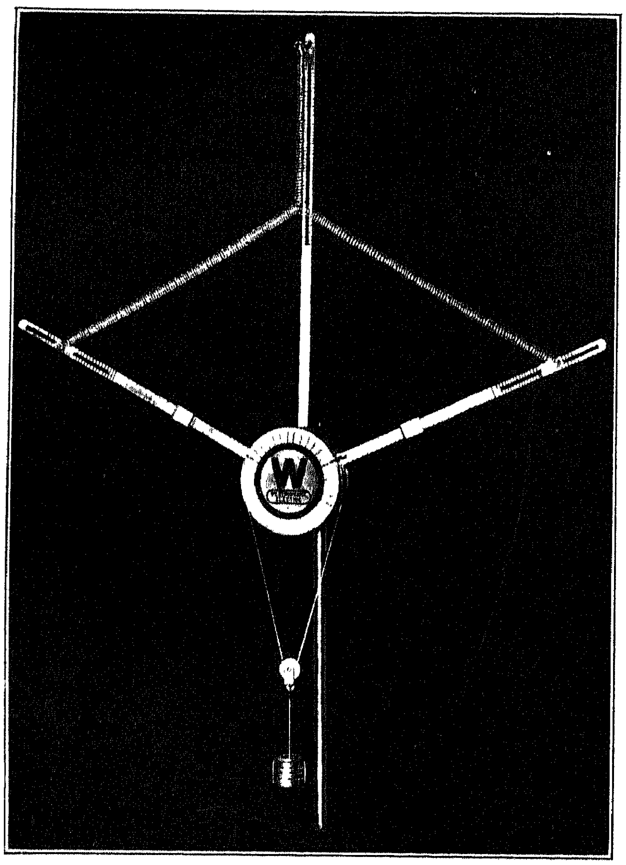

FIG. 2—MECHANICAL MODEL INCLUDING INTERMEDIATE CONDENSER

to lower series impedance in the electrical system, and also by using longer lever arms which correspond to higher transmission voltages. However, probably the easiest way of increasing the power limit of this mechanical system is to insert a mechanical prop at an intermediate point. If a rigid prop is located at the mid-point, the mechanical system can transmit twice as much power as before. The electrical equivalent is a synchronous condenser of zero impedance. Ordinary synchronous condensers may be represented by the introduction of a spring between the extremity of a movable arm representing the internal voltage of the condenser and the point on the spring corresponding to the location of the condenser as indicated in Fig. 2.

It is not feasible to go into a detailed explanation of the performance of the mechanical model for steady state or transient conditions. This description of the mechanical model has been given here to assist in a physical interpretation of the analytical methods presented in the paper. Further information may be obtained by referring to the article by Mr. Griscom.

The present paper incorporates the results of investigations to determine the stability characteristics of systems with intermediate condensers. These investigations necessarily have included work on the general stability problem of systems involving three or more sources of synchronous e. m. f. In fact, the present study is concerned chiefly with an analytical investigation of the static limits of network power systems disclosing methods applicable to the intermediate condenser station problem.

It is desirable at the outset to point out the limitations of the investigations. The present paper is confined to static limits. Static limits are important because they may be approached under emergency conditions even though the system is designed to operate well below these limits normally. It is recognized that stability limits under transient conditions occur for smaller values of transmitted power. The authors presented a step-by-step method† applicable for the determination of the transient limits of transmission systems including intermediate condensers. It may be pointed out that static limits are best investigated by the application of a criterion obtained on the basis of small transients. In regard to the intermediate condenser station problem, specifically, the nature of the problem lends itself well to a general investigation from the standpoint of static limits, whereas it does not lend itself to a general investigation of transient limits. Two of our colleagues, Messrs. R. C. Bergvall and P. H. Robinson will present in the near future a paper describing the application of the mechanical model to the solution of stability problems of net-work power systems. The authors hold the opinion that this method offers real promise for the solution of practical problems involving the intermediate condenser station as well as the problems of the closely connected power system.

The general outline of the paper is as follows:

1. General representation of systems.
2. Discussion of the assumptions involved.
3. Stability limit of the two-synchronous-machine case.
4. Calculation of the stability limits of straight-away transmission systems.
5. Static limit of the three-synchronous-machine case including a study of one intermediate condenser station.
6. Stability limits of the four-synchronous-machine case.
7. Calculation of power limits with one and two intermediate condenser stations.

†Bibliography, Item 12.

General Representation of Systems

In general, the solution of any physical problem is reached by the solution of equations, the number of these equations being equal to the number of unknown quantities in the problem. This is also true for a-c. networks with fixed constants. Because of the linear nature of the first and second laws of Kirchhoff, which alone are necessary for a solution, the simultaneous equations are always linear, with constant coefficients. The solution for the terminal currents in terms of the terminal voltages of an n terminal network can always be reduced to the following form*

$$\left.\begin{aligned}
\mathbf{I}_a &= \mathbf{Y}_{aa}\,\mathbf{E}_a - \mathbf{Y}_{ab}\,\mathbf{E}_b - \mathbf{Y}_{ac}\,\mathbf{E}_c \;.\;.\;.\;.\;.\; - \mathbf{Y}_{an}\,\mathbf{E}_n \\
\mathbf{I}_b &= -\,\mathbf{Y}_{ba}\,\mathbf{E}_a + \mathbf{Y}_{bb}\,\mathbf{E}_b - \mathbf{Y}_{bc}\,\mathbf{E}_c \;.\;.\;.\;.\; - \mathbf{Y}_{bn}\,\mathbf{E}_n \\
\mathbf{I}_n &= -\,\mathbf{Y}_{na}\,\mathbf{E}_a - \mathbf{Y}_{nb}\,\mathbf{E}_b - \mathbf{Y}_{nc}\,\mathbf{E}_c \;.\;.\;.\;.\; + \mathbf{Y}_{nn}\,\mathbf{E}_n
\end{aligned}\right\} \quad (1)$$

in which the coefficients $\mathbf{Y}_{aa}, \mathbf{Y}_{bb} \ldots . \mathbf{Y}_{nn}$ are termed self admittances, and the coefficients $\mathbf{Y}_{ab}$, $\mathbf{Y}_{mn}$, etc., are termed mutual admittances. It can be shown that $\mathbf{Y}_{mn}$ is equal to $\mathbf{Y}_{nm}$. The network is then completely defined as far so the terminal conditions are concerned by n self admittances and $\frac{n}{2}\ (n - 1)$ mutual admittances. A two terminal network will reduce to a network of two self admittances and one mutual admittance, a three-terminal network will reduce to a network of three self admittances, and three mutual admittances. The physical significance of these notions may be illustrated by considering in more detail a three terminal network. The equations for this case are

$$\left.\begin{aligned}
\mathbf{I}_a &= \mathbf{Y}_{aa}\,\mathbf{E}_a - \mathbf{Y}_{ab}\,\mathbf{E}_b - \mathbf{Y}_{ca}\,\mathbf{E}_c \\
\mathbf{I}_b &= -\,\mathbf{Y}_{ab}\,\mathbf{E}_a + \mathbf{Y}_{bb}\,\mathbf{E}_b - \mathbf{Y}_{bc}\,\mathbf{E}_c \\
\mathbf{I}_c &= -\,\mathbf{Y}_{ca}\,\mathbf{E}_a - \mathbf{Y}_{bc}\,\mathbf{E}_b + \mathbf{Y}_{cc}\,\mathbf{E}_c
\end{aligned}\right\} \quad (2)$$

Now, referring to Fig. 3 it will be seen that the above

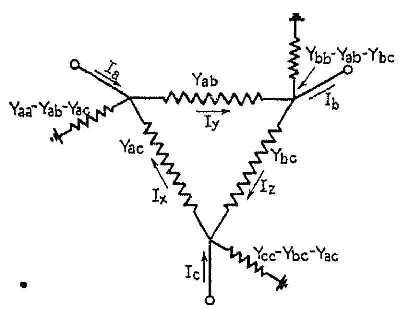

Fig. 3—Admittance Diagram Representing General Case for a Three-Terminal Network

equations represent the solution of the network indicated. The truth of this statement can be shown as follows:

Since

$$\mathbf{E}_a = \mathbf{E}_b + \frac{1}{\mathbf{Y}_{ab}}\, I_x$$

then

$$\mathbf{I}_x = +\,\mathbf{Y}_{ab}\,\mathbf{E}_a - \mathbf{Y}_{ab}\,\mathbf{E}_b$$

Similarly

$$\mathbf{I}_z = +\,\mathbf{Y}_{ca}\,\mathbf{E}_c - \mathbf{Y}_{ca}\,\mathbf{E}_a$$

Equating the currents at the junction a

$$\begin{aligned}
\mathbf{I}_a &= (\mathbf{Y}_{aa} - \mathbf{Y}_{ab} - \mathbf{Y}_{ca})\,\mathbf{E}_a + (\mathbf{Y}_{ab}\,\mathbf{E}_a - \mathbf{Y}_{ab}\,\mathbf{E}_b) \\
&\quad - (\mathbf{Y}_{ca}\,\mathbf{E}_c - \mathbf{Y}_{ca}\,\mathbf{E}_a) \\
&= \mathbf{Y}_{aa}\,\mathbf{E}_a - \mathbf{Y}_{ab}\,\mathbf{E}_b - \mathbf{Y}_{ca}\,\mathbf{E}_c
\end{aligned}$$

This is identical to the equation defining $\mathbf{I}_a$. The

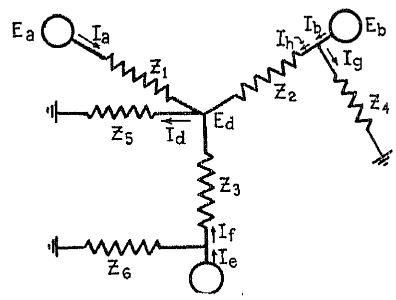

Fig. 4—Diagram Representing Particularly Case of a Three-Terminal Network

expressions for $\mathbf{I}_b$ and $\mathbf{I}_c$ can be proved in a similar manner.

To insure a thorough understanding of the significance of these constants, consider the particular example of a three terminal network, shown in Fig. 4. This represents three generators feeding the load represented by $\mathbf{Z}_5$ through impedances. In addition, two of the machines have loads taken off their terminals. The equations for the network of Fig. 4 may be written as follows:

$$\mathbf{I}_a = \frac{1}{\mathbf{Z}_1}\,\mathbf{E}_a - \frac{1}{\mathbf{Z}_1}\,\mathbf{E}_d = \mathbf{Y}_1\,\mathbf{E}_a - \mathbf{Y}_1\,\mathbf{E}_d$$

$$\mathbf{I}_h = \frac{1}{\mathbf{Z}_2}\,\mathbf{E}_b - \frac{1}{\mathbf{Z}_2}\,\mathbf{E}_d = \mathbf{Y}_2\,\mathbf{E}_b - \mathbf{Y}_2\,\mathbf{E}_d$$

$$\mathbf{I}_f = \frac{1}{\mathbf{Z}_3}\,\mathbf{E}_c - \frac{1}{\mathbf{Z}_3}\,\mathbf{E}_d = \mathbf{Y}_3\,\mathbf{E}_c - \mathbf{Y}_3\,\mathbf{E}_d$$

$$\mathbf{I}_d = \qquad + \frac{1}{\mathbf{Z}_5}\,\mathbf{E}_d = \qquad \mathbf{Y}_5\,\mathbf{E}_d$$

. . . .

Summing the currents at the junction point

$$\mathbf{I}_a + \mathbf{I}_h + \mathbf{I}_f - \mathbf{I}_d = 0$$

Substituting and solving for $\mathbf{E}_d$

$$\mathbf{E}_d = \frac{\mathbf{Y}_1\,\mathbf{E}_a + \mathbf{Y}_2\,\mathbf{E}_b + \mathbf{Y}_3\,\mathbf{E}_c}{\mathbf{Y}_1 + \mathbf{Y}_2 + \mathbf{Y}_3 + \mathbf{Y}_5}$$

From which

$$\mathbf{I}_a = \mathbf{Y}_1\,\mathbf{E}_a - \mathbf{Y}_1\,\frac{\mathbf{Y}_1\,\mathbf{E}_a + \mathbf{Y}_2\,\mathbf{E}_b + \mathbf{Y}_3\,\mathbf{E}_c}{\mathbf{Y}_1 + \mathbf{Y}_2 + \mathbf{Y}_3 + \mathbf{Y}_5}$$

*Complex quantities will be designated in this paper by a bold face roman type. The conjugate will be designated by old English type. Italic type indicates absolute value.

$$\mathbf{I}_b = (\mathbf{Y}_2 + \mathbf{Y}_4)\,\mathbf{E}_b - \mathbf{Y}_2 \frac{\mathbf{Y}_1\,\mathbf{E}_a + \mathbf{Y}_2\,\mathbf{E}_b + \mathbf{Y}_3\,\mathbf{E}_c}{\mathbf{Y}_1 + \mathbf{Y}_2 + \mathbf{Y}_3 + \mathbf{Y}_5}$$

$$\mathbf{I}_c = (\mathbf{Y}_3 + \mathbf{Y}_6)\,\mathbf{E}_c - \mathbf{Y}_3 \frac{\mathbf{Y}_1\,\mathbf{E}_a + \mathbf{Y}_2\,\mathbf{E}_b + \mathbf{Y}_3\,\mathbf{E}_c}{\mathbf{Y}_1 + \mathbf{Y}_2 + \mathbf{Y}_3 + \mathbf{Y}_5}$$

In this particular case, equating like coefficients:

$$\mathbf{Y}_{aa} = \mathbf{Y}_1 \quad \frac{\mathbf{Y}_1^2}{\mathbf{Y}_1 + \mathbf{Y}_2 + \mathbf{Y}_3 + \mathbf{Y}_5}$$

$$\mathbf{Y}_{ab} = \frac{\mathbf{Y}_1\,\mathbf{Y}_2}{\mathbf{Y}_1 + \mathbf{Y}_2 + \mathbf{Y}_3 + \mathbf{Y}_5}$$

$$\mathbf{Y}_{ac} = \frac{\mathbf{Y}_3\,\mathbf{Y}_1}{\mathbf{Y}_1 + \mathbf{Y}_2 + \mathbf{Y}_3 + \mathbf{Y}_5}$$

$$\mathbf{Y}_{bb} = \mathbf{Y}_2 + \mathbf{Y}_4 - \frac{\mathbf{Y}_2^2}{\mathbf{Y}_1 + \mathbf{Y}_2 + \mathbf{Y}_3 + \mathbf{Y}_5}$$

$$\mathbf{Y}_{cc} = \mathbf{Y}_3 + \mathbf{Y}_6 - \frac{\mathbf{Y}_3^2}{\mathbf{Y}_1 + \mathbf{Y}_2 + \mathbf{Y}_3 + \mathbf{Y}_5}$$

$$\mathbf{Y}_{bc} = \frac{\mathbf{Y}_3\,\mathbf{Y}_2}{\mathbf{Y}_1 + \mathbf{Y}_2 + \mathbf{Y}_3 + \mathbf{Y}_5}$$

In the above example, only ordinary impedances were used. The general method, however, is not limited by such restrictions, but can be applied to the representation of lines with distributed constants combined in the most complicated manner. Using the method of General Circuit Constants* developed by Messrs. Evans and Sels, the current at the sending and receiving ends of every branch in the network can always be expressed, respectively, as

$$\left.\begin{aligned} \mathbf{I}_s &= \frac{\mathbf{D}}{\mathbf{B}}\,\mathbf{E}_s - \frac{1}{\mathbf{B}}\,\mathbf{E}_r \\[2ex] \mathbf{I}_r &= \frac{\mathbf{E}_s}{\mathbf{B}} - \frac{\mathbf{A}}{\mathbf{B}}\,\mathbf{E}_r \end{aligned}\right\} \qquad (3)$$

Summing the currents at a junction point and equating to zero, an expression for the voltage at the junction point can be obtained in terms of the voltage at the adjacent junction points. Following this procedure and eliminating the voltages at all the junction points, equations can be derived expressing the currents at terminals in terms of the terminal voltages. Care must be exercised to prevent an error in sign as the method of self and mutual admittances just described assumes the current as positive when flowing *into* the network at *every terminal,* whereas the method of General Circuit Constants assumes current as positive when flowing *into* the network at supply and *out of* the network at the receiving end.

* Bibliography, Item 2.

Discussion of the Assumptions Involved

The general method described in the previous section is the only one available for analytical calculation of stability limits of power system networks. Transformers, reactors, and lines may be represented in the usual manner by general networks with constant impedance and admittance branches. The accuracy of the general method depends upon the justification of the following approximations:

1. Synchronous machines may be represented by a source of voltage and a series impedance.
2. Loads may be represented by shunt admittances alone or in combination with synchronous machines.

The above items will be considered individually.

Representation of Synchronous Machines

The representation of a synchronous machine by a source of synchronous e. m. f. and a series impedance is a commonly recognized device. The value of the impedance and voltage, however, differ for various applications. For example, in short circuit calculations, the initial symmetrical value of the short circuit current is estimated on the basis that the synchronous machine is represented by a voltage corresponding to the air-gap flux and an impedance called "transient impedance"; while the sustained value of short circuit current is estimated on the basis that the synchronous machine is represented by a voltage corresponding to the excitation and an impedance called the "synchronous impedance." In stability calculations it is necessary to know not only the magnitude of machine voltage and machine impedance but also the angular relation between the terminal voltage and position of the rotor.

The machine voltage to be employed in static stability calculations depends upon whether the excitation is constant or changes importantly. For the purpose of this paper the excitation will be assumed constant, the value of the excitation being so chosen as to regulate the terminal voltage at any desired value. Mention should be made of the fact that when an automatic voltage regulator and an exciter having an extremely quick response are employed, the excitation can be increased at a rate that is sufficiently rapid to increase the static limits materially. This possibility was first recognized by Mr. E. B. Shand* and subsequently proved by calculations and experiments by the authors in 1925†. Experimental verification has also been secured by Messrs. Doherty and Nickle‡. Determination of whether a given system under control of voltage regulators is stable can be obtained by the application of the step-by-step method of transient analysis§. This discussion of the static limits with regulators has been given at some length because the

*Bibliography, Item 5.
†Bibliography, Items 12 and 13.
‡Bibliography, Item 16.
§Bibliography, Item 12.

methods described in the paper for the determination of static limits without regulators may be employed to give approximate limits with regulators by the use of a voltage and an impedance intermediate between the synchronous impedance and excitation voltage on the one hand and the air gap voltage and leakage or transient impedance on the other hand, the faster the response of the excitation system the closer it approaches the latter value.

The impedance to be employed to represent a synchronous machine with a definite excitation is not a constant quantity and is affected by saturation. Where salient pole machines are employed another effect must be considered, namely, the saliency effect arising from non-uniform air-gap reluctance. As a consequence the machine impedance varies in magnitude and also in phase angle as a function of the real and reactive power delivered.

The synchronous machine is best analyzed by the two-reaction method due to Blondel. This method as applied to a synchronous generator is shown graphically in Fig. 5. Because of the relative unimportance of armature resistance in stability calculations this factor

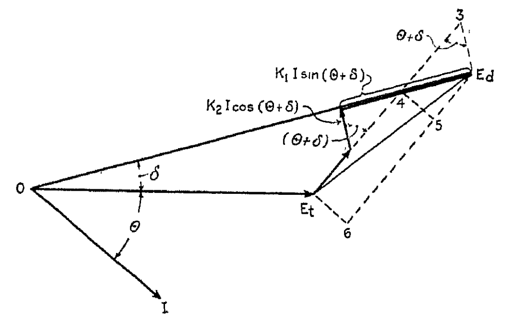

FIG. 5—VECTOR DIAGRAM FOR SYNCHRONOUS GENERATOR

E_t = Terminal voltage
I = Armature current
X_L = Leakage reactance
K_1 = Reactance equivalent of armature reaction along the main axis
K_2 = Reactance equivalent of armature reaction along the cross axis
E_d = Excitation voltage
θ = Angle between E_t and I
= Angle between E_d and E_t

has been neglected. The figure is self explanatory in indicating the fundamental relations used by Blondel in his classic treatment. The effective machine impedance may be defined as that value which multiplied by I vectorially will produce the voltage drop $\mathbf{Z}_s\mathbf{I}$. This impedance may be obtained as follows:

Distance

$$1-3 = K_1 I$$
$$1-4 = K_2 I$$
$$3-4 = (K_1 - K_2) I$$
$$4-E_d = (K_1 - K_2) I \sin(\theta+\delta)$$
$$E_t - 6 = 4-5$$
$$= (K_1 - K_2) I \sin(\theta+\delta)\cos(\theta+\delta)$$
$$= \frac{(K_1 - K_2)}{2} I \sin 2(\theta+\delta)$$
$$6-5 = (X_L + K_2) I$$
$$5-E_d = (K_1 - K_2) I \sin^2(\theta+\delta)$$
$$= \frac{(K_1 - K_2)}{2} I [1 - \cos 2(\theta+\delta)]$$

The effective machine impedance* may now be written as:

$$\mathbf{Z}_s = \frac{1}{I}\Big[(E_t - 6) + j(6-5) + j(5-E_d)\Big]$$
$$= \frac{K_1 - K_2}{2}\sin 2(\theta+\delta) + j(X_L + K_2)$$
$$+ j\frac{(K_1 - K_2)}{2}[1 - \cos 2(\theta+\delta)]$$
$$= j\left[X_L + \frac{K_1 + K_2}{2}\right] + \left(\frac{K_1 - K_2}{2}\right)\Big[\sin 2(\theta+\delta) - j\cos 2(\theta+\delta)\Big] \quad (4)$$

The above relation may be expressed in different notation for reactances as follows:†

$X_d = X_L + K_1$, synchronous reactance, direct axis

$X_q = X_L + K_2$, synchronous reactance, cross axis

so that the impedance becomes:

$$\mathbf{Z}_s = +j\left(\frac{X_d + X_q}{2}\right) + \left(\frac{X_d - X_q}{2}\right)\Big[\sin 2(\theta+\delta) - j\cos 2(\theta+\delta)\Big] \quad (5)$$

Examination of equations (4) or (5) appear to make it difficult to determine the proper value of machine impedance. However, the fictitious resistance term $\frac{X_d - X_q}{2}\sin 2(\theta+\delta)$ is positive in a generator and negative in a motor. Consequently for the case of two similar machines operating at equal excitation and neglecting armature resistance, the total effective impedance is:

$$\mathbf{Z}_s = 0 + j[(X_d + X_q) - (X_d - X_q)\cos 2(\theta+\delta)]$$

In such a case the current is in phase with the terminal voltage so that $\theta = 0$. Hence

$$\mathbf{Z}_s = 0 + j\left[\frac{(X_d + X_q)}{2} - \frac{(X_d - X_q)}{2}\cos 2\delta\right] \quad (6)$$

For such a system, pull-out will occur at about $\delta = 45$ deg. so that the value of synchronous reactance to be used is

*Bibliography, Item 14.
†Bibliography, Item 15.

$$\mathbf{Z}_s = j\,\frac{X_d + X_q}{2} = j\left(X_L + \frac{K_1 + K_2}{2}\right) \qquad (7)$$

The effect of line reactance may be included by increasing the X_L term by an amount equal to one-half of the line reactance. This is equivalent to considering the machine reactance as that defined by equation (7) even though that equation was derived for the assumption of zero line reactance. For the normal machine in which $K_2 = 0.5\,K_1$, this defines Z_s as equal to $X_L + 0.75\,K_1$.

The general representation of systems by means of

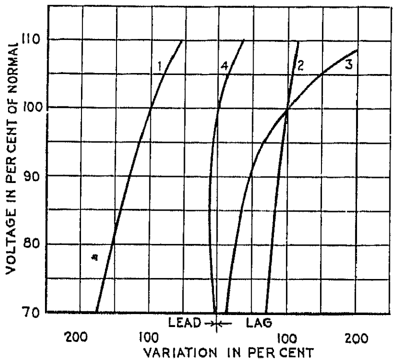

FIG. 6—VARIATION OF REACTIVE KV-A. WITH VOLTAGE

1. Synchronous motor—75 per cent load, 85 per cent power factor. lead (at normal voltage)
2. Induction motor, 75 per cent load, 79 per cent power factor lag (average at normal voltage)
3. Transformer exciting kv-a.
4. Synchronous converter (reactive kv-a. in per cent of machine rating),

impedance networks as defined by equation (1) require that all impedances in the system be constant and independent of the current, voltage, or phase relation between currents and voltages. The impedance of machines, as defined by equation (5) however, is not independent of the angles between current and terminal and excitation voltages. For this reason, while this impedance is accurate for most purposes, it is not theoretically correct but is sufficiently accurate for substitution in formulas for the criterion of stability to be discussed later.

The acceleration of the rotor of a synchronous machine varies directly as the difference of the torque due to the prime mover and the magnetic torque reacting on the rotor and inversely as the mechanical inertia of the rotor. In stability calculation, the actual velocity is so nearly constant that the acceleration is proportional to the difference in power input and output. A convenient formula for obtaining the acceleration is derived in Appendix III which is as follows:

$$\alpha = \frac{180\,f}{W}\,\Delta P \qquad (8)$$

LOAD CHARACTERISTICS

The load at the receiving end of a transmission system consists of induction motors, lighting, synchronous motors, and synchronous converters with the first named predominating.

The various types of load have different characteristics. With synchronous and induction motors, the true power demand may be assumed to remain constant with variation in voltage, whereas lighting and synchronous converter load will vary as the square of the voltage. The reactive power demand varies greatly with the different types of load and the variation of reactive power with terminal voltage for typical loads are shown in the curves of Fig. 6.*

It is impractical to consider a multitude of individual loads, and it therefore becomes necessary to use some composite load characteristics such as shown in Fig. 7. These load characteristics must also take into account the effect of local supply lines and transformers impedance and admittances. Such a characteristic load curve is difficult to handle analytically so it is pertinent to consider suitable approximations such as the shunt admittance of constant value indicated by the dotted line of Fig. 7. It should be noted that the constant admittance method is optimistic so far as true power is concerned and pessimistic in regard to reactive power changes. The justification for this approximation follows from the application of an accurate method to a number of special cases. The accurate solution is of course obtained by employing the actual data as to the rates of change of real and reactive power as described

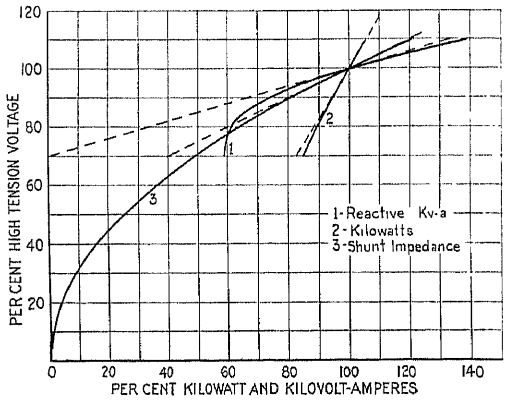

FIG. 7—TYPICAL LOAD CHARACTERISTIC CURVE

in the Appendix II. Calculations were made on a simple transmission system for a variety of load conditions. The study of these results given in the Appendix indicates that shunt admittances represent not only a desirable approximation but a highly accurate one as well. Furthermore, it is possible to combine shunt admittance with the synchronous machine characteristics to obtain a combination still more nearly representative of all receiving end characteristics.

TWO MACHINE PROBLEM

The problem involving two sources of synchronous a-c. voltages has been termed the "Two Machine

*Bibliography, Item 12.

Problem." The solution given here represents the general case for any two synchronous machines connected to networks in which the load can be represented by pure admittances or shaft loads on the synchronous machines. These machines may be operating as two generators, as one generator and one motor, or as one generator and a condenser. The current at the terminals of the machines can always be expressed in terms of the internal voltages by the following equations:

$$\left.\begin{aligned} \mathbf{I}_a &= \mathbf{Y}_{aa}\,\mathbf{E}_a - \mathbf{Y}_{ab}\,\mathbf{E}_b \\ \mathbf{I}_b &= -\,\mathbf{Y}_{ab}\,\mathbf{E}_a + \mathbf{Y}_{bb}\,\mathbf{E}_b \end{aligned}\right\} \tag{9}$$

in which currents in the positive sense are taken as flowing *out* of the machine and *into* the network, $\mathbf{I}_a$ and $\mathbf{I}_b$ are line currents and $\mathbf{E}_a$ and $\mathbf{E}_b$ are star voltages which are considered as being secured rigidly to the rotor so that their time rates of change are determined by the time rates of change of their rotors.

The real and reactive components of power output of the two generators are:

$$\begin{aligned} P_a + j\,Q_a &= 3\,\mathbf{E}_a \mathfrak{I}_a \\ &= 3\,\mathfrak{Y}_{aa} E_a^2 - \mathfrak{E}\,\mathfrak{Y}_{ab}\,\mathbf{E}_a\,\mathfrak{E}_b \\ P_b + j\,Q_b &= 3\,\mathbf{E}_b \mathfrak{I}_b \\ &= -\,3\,\mathfrak{Y}_{ab}\,\mathfrak{E}_a\,\mathbf{E}_b + 3\,\mathfrak{Y}_{bb} E_b^2 \end{aligned}$$

or in terms of their line to line voltages:

$$\left.\begin{aligned} P_a + j\,Q_a &= \mathfrak{Y}_{aa} E_{\mathrm{A}}^2 - \mathfrak{Y}_{ab}\,\mathbf{E}_{\mathrm{A}}\,\mathfrak{E}_{\mathrm{B}} \\ P_b + j\,Q_b &= -\,\mathfrak{Y}_{ab}\,\mathfrak{E}_{\mathrm{A}}\,\mathbf{E}_{\mathrm{B}} + \mathfrak{Y}_{bb} E_{\mathrm{B}}^2 \end{aligned}\right\} \tag{10}$$

Let

$$\left.\begin{aligned} \mathbf{E}_{\mathrm{A}} &= E_{\mathrm{A}}\,\epsilon^{j\phi_{\mathrm{A}}} \\ \mathbf{E}_{\mathrm{B}} &= E_{\mathrm{B}}\,\epsilon^{j\phi_{\mathrm{B}}} \\ \mathbf{Y}_{ab} &= Y_{ab}\,\epsilon^{j\phi_1} \\ \mathbf{Y}_{aa} &= Y_{aa}\,\epsilon^{j\phi_7} \\ \mathbf{Y}_{bb} &= Y_{bb}\,\epsilon^{j\phi_8} \end{aligned}\right\} \tag{11}$$

then

$$\left.\begin{aligned} P_a + j\,Q_a &= Y_{aa} E_{\mathrm{A}}^2\,\epsilon^{-j\phi_7} \\ &\quad - Y_{ab} E_{\mathrm{A}} E_{\mathrm{B}}\,\epsilon^{j(\phi_{\mathrm{A}} - \phi_{\mathrm{B}} - \phi_1)} \\ P_b + j\,Q_b &= -\,Y_{ab} E_{\mathrm{A}} E_{\mathrm{B}}\,\epsilon^{j(\phi_{\mathrm{B}} - \phi_{\mathrm{A}} - \phi_1)} \\ &\quad + Y_{bb} E_{\mathrm{B}}^2\,\epsilon^{-j\phi_8} \end{aligned}\right\} \tag{12}$$

and since $\epsilon^{j\theta} = \cos\theta + j\sin\theta$

$$\left.\begin{aligned} P_a &= Y_{aa} E_{\mathrm{A}}^2 \cos\phi_7 \\ &\quad - Y_{ab} E_{\mathrm{A}} E_{\mathrm{B}} \cos(\phi_{\mathrm{A}} - \phi_{\mathrm{B}} - \phi_1) \\ P_b &= -\,Y_{ab} E_{\mathrm{A}} E_{\mathrm{B}} \cos(\phi_{\mathrm{A}} - \phi_{\mathrm{B}} + \phi_1) \\ &\quad + Y_{bb} E_{\mathrm{B}}^2 \cos\phi_8 \end{aligned}\right\} \tag{13}$$

These equations define the electrical output at a and at b. The mechanical input will be designated by P_{ga} and P_{gb} in which input as for a generator will be considered positive and input as for a motor having a shaft load as negative. The difference between the input and output of say a turbine-generator set is thus expressed by $P_{ga} - P_a$. This can be converted to acceleration of the rotor by means of equation (8), so that α_{A} or $\dfrac{d^2\,\phi_{\mathrm{A}}}{d\,t^2}$, is equal to

$$\begin{aligned} \alpha_{\mathrm{A}} &= \frac{d^2\,\phi_{\mathrm{A}}}{d\,t^2} = \frac{180\,f}{W_a}\,(P_{ga} - P_a) \\ &= \frac{180\,f}{W_a}\,P_{ga} - \frac{180\,f}{W_a}\,Y_{aa} E_{\mathrm{A}}^2 \cos\phi_7 + \\ &\quad + \frac{180\,f}{W_a}\,Y_{ab} E_{\mathrm{A}} E_{\mathrm{B}} \cos(\phi_{\mathrm{A}} - \phi_{\mathrm{B}} - \phi_1) \end{aligned} \tag{14}$$

$$\begin{aligned} \alpha_{\mathrm{B}} &= \frac{d^2\,\phi_{\mathrm{B}}}{d\,t^2} = \frac{180\,f}{W_b}\,(P_{gb} - P_b) \\ &= \frac{180\,f}{W_b}\,P_{gb} - \frac{180\,f}{W_b}\,Y_{bb} E_{\mathrm{B}}^2 \cos\phi_8 \\ &\quad + \frac{180\,f}{W_b}\,Y_{ab} E_{\mathrm{A}} E_{\mathrm{B}} \cos(\phi_{\mathrm{A}} - \phi_{\mathrm{B}} + \phi_1) \end{aligned} \tag{15}$$

These expressions determine the rate of change in the absolute position of the voltage vectors. In the final analysis, however, it is the variation of the difference in angle between the two voltages, the phase angle difference, that is really important. So long as the phase difference between the two voltages does not exceed a certain value the actual changes in their position in space is unimportant.

Let

$$\phi_{\mathrm{A}} - \phi_{\mathrm{B}} = \phi \tag{16}$$

$$\frac{d^2\,\phi}{d\,t^2} = \frac{d^2\,\phi_{\mathrm{A}}}{d\,t^2} - \frac{d^2\,\phi_{\mathrm{B}}}{d\,t^2} = \alpha_{\mathrm{A}} - \alpha_{\mathrm{B}} = \alpha \tag{17}$$

From equations (14) and (15)

$$\begin{aligned} \alpha = 180\,f \Bigg\{ & \frac{P_{ga}}{W_a} - \frac{P_{gb}}{W_b} + \frac{Y_{bb} E_{\mathrm{B}}^2}{W_b} \cos\phi_3 \\ & - \frac{Y_{aa} E_{\mathrm{A}}^2}{W_a} \cos\phi_1 + Y_{ab} E_{\mathrm{A}} E_{\mathrm{B}} \\ & \left[- \left(\frac{1}{W_a} - \frac{1}{W_b} \right) \cos\phi_1 \cos\phi \right. \\ & \left. + \left(\frac{1}{W_a} + \frac{1}{W_b} \right) \sin\phi_1 \sin\phi \right] \Bigg\} \end{aligned} \tag{18}$$

This equation completely determines the oscillation between the machines resulting from a disturbance for the given circuit conditions, voltages, inertias, and governor settings. Circuit conditions, inertia of machines, shaft loads of motors, and prime mover inputs of generators can be assumed constant, the last named because of the relatively sluggish action of governors. The voltages appearing in the equations are machine voltages which are assumed constant in magnitude.

The above equation can be solved by elliptic functions or by step-by-step methods. For small variations from the mean angle the following method may be used.

$$\Delta \alpha = \frac{d\alpha}{d\phi} \Delta \phi$$

$$= 180 f\, Y_{ab} E_a E_b \left[-\left(\frac{1}{W_a} - \frac{1}{W_b} \right) \cos \phi_1 \sin \phi + \right.$$

$$\left. + \left(\frac{1}{W_a} + \frac{1}{W_b} \right) \sin \phi_1 \cos \phi \right] \Delta \phi \qquad \textbf{(19)}$$

It is interesting to note that only the mutual admittance enters this equation, the two self impedances disappearing because they are not associated with terms that vary with the angle.

In analyzing the conditions for stable operation at a given operating point several criteria suggest themselves. One of the rotors can be displaced forcibly from its position of equilibrium and the relations analyzed to determine whether it will return to its original position. An increment of load could be placed on the shaft of one unit and the conditions investigated for stable operation. Another disturbance suggests itself in decreasing the network load by changing the network constants. The latter two involve a change in frequency or governor setting to determine the final steady state operating conditions. For this reason the change in angular position constituting the disturbing factor will be selected.

The criterion for stability shall be that the system return to its original position after a slight displacement of the angle between the machines. Let ϕ_0 be the steady state angle and θ the departure of ϕ from this angle, then

$$\phi = \phi_0 + \theta \qquad \textbf{(20)}$$

$\Delta \phi$ is then equal to θ for small value of θ and $\alpha = \frac{d^2 \phi}{d t^2} = \frac{d^2 \theta}{d t^2}$. Since the acceleration is zero for $\phi = \phi_0$, everything being balanced for this particular value, then $\Delta \alpha = \alpha$ for small values of α.

Equation (**19**) may now be written

$$\frac{d^2 \theta}{dt^2} = 180 f\, Y_{ab} E_a E_b \left[-\left(\frac{1}{W_a} - \frac{1}{W_b} \right) \cos \phi_1 \sin \phi_0 \right.$$

$$\left. \left(\frac{1}{W_a} + \frac{1}{W_b} \right) \sin \phi_1 \cos \phi_0 \right] . \ \theta \qquad \textbf{(21)}$$

This has the same form as the simple differential equation

$$\frac{d^2 \theta}{dt^2} = K \theta \qquad \textbf{(22)}$$

which is the equation for simple harmonic motion so long as K is negative. The condition then that the motion resulting from a disturbance be oscillatory and not continue with increasing angle and finally pull out is that the coefficient of θ be negative; then for any small displacement θ the rotors will always return to their original relative position. Since the quantity $180 f\, Y_{ab} E_a E_b$ is positive the condition for stable operation reduces to the relation that

$$\left(\frac{1}{W_a} + \frac{1}{W_b} \right) \sin \phi_1 \cos \phi_0$$

$$- \left(\frac{1}{W_a} - \frac{1}{W_b} \right) \cos \phi_1 \sin \phi_0 < 0 \qquad \textbf{(23)}$$

The limiting condition is reached for that value of ϕ_0 for which

$$\left(\frac{1}{W_a} + \frac{1}{W_b} \right) \sin \phi_1 \cos \phi_0$$

$$- \left(\frac{1}{W_a} - \frac{1}{W_b} \right) \cos \phi_1 \sin \phi_0 = 0$$

or for

$$\tan \phi_0 = \frac{W_b + W_a}{W_b - W_a} \tan \phi_1 \qquad \textbf{(24)}$$

It can be seen from this that the limiting angle is a function of the inertia of the two machines and of the argument of the complex number representing the mutual admittance Y_{ab}. This result is contrary to the previously accepted theory which neglected the influence of the relative values of the inertia.

For

$$W_a = \infty$$

$$\tan \phi_0 = - \tan \phi_1$$

$$\phi_0 = - \phi_1 + n \pi$$

where n is any integral number.

For $W_b = \infty$

$$\phi_0 = \phi_1 + m \pi$$

For $W_a = W_b$

$$\phi_0 = \pi / 2 \qquad \textbf{(25)}$$

For those cases usually met in practise in which a is the sending end and b the receiving end of a transmission system

$$n = 0 \text{ and } m = 1, \text{ so that}$$

for

$$W_a = \infty, \ \phi_0 = - \phi_1 \qquad \textbf{(26)}$$

and for

$$W_b = \infty, \ \phi_0 = \pi + \phi_1 \qquad \textbf{(27)}$$

These general considerations, perhaps, may be seen more clearly by analyzing the expressions for α_a and α_b in the light of the power circle diagrams. Consider machine a as a generator and machine b as a motor connected by a simple impedance **Z**. The motor shall be loaded by a shaft load of essentially constant power. (see Fig. 8) The coefficients for this case will then be:

$$\mathbf{Y}_{aa} = \mathbf{Y}_{ab} = \mathbf{Y}_{bb} = \frac{1}{R + j X} = \frac{1}{Z \epsilon^{j\psi}} = \frac{1}{Z} \epsilon^{-j\psi}$$

so that equations (**12**) become

$$P_a + j\,Q_a = \frac{1}{Z}\,E_A^2\,\epsilon^{j\psi} - \frac{1}{Z}\,E_A\,E_B\,\epsilon^{j(\phi+\psi)} \qquad (28)$$

$$P_b + j\,Q_b = -\frac{1}{Z}\,E_A\,E_B\,\epsilon^{j(-\phi+\psi)} + \frac{1}{Z}\,E_B^2\,\epsilon^{j\psi} \qquad (29)$$

Reversing the positive reference of current flow at B

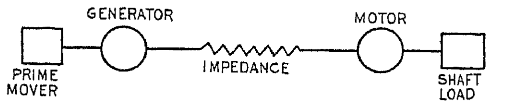

Fig. 8—Simple Power System

to correspond to the more usual practise the power expression for B becomes:

$$P_{b1} + j\,Q_{b1} = +\frac{1}{Z}\,E_A\,E_B\,\epsilon^{j(-\phi+\psi)} - \frac{1}{Z}\,E_B^2\,\epsilon^{j\psi} \qquad (30)$$

Equations (28) and (29) can be plotted in the usual form of power circle diagrams shown in Fig. 9. The point a, being the center of the sending-end circle, is determined by the first term in equation (28); the second term may be drawn with a as center and radius equal to the absolute value of the second term. For $\phi = 0$ the line will lie along $o\,a$. This line constitutes the reference line. For other values of ϕ the particular angle is measured from this line, positive angles rotating the vector counter-clockwise. The receiver circle is plotted in a similar manner with center at b determined by the last term of equation (30). Positive angles are measured in clockwise rotation from $b\,o$. Now suppose the systems were operating at the point c on the sending end circle which corresponds to d on the receiving circle. The governor would be set for the power corresponding to c and the power, or torque since speed changes so slightly, on the motor would correspond to point d. Any slight instantaneous change in the operating angle would change the operating points to c' and d'. Since the governor setting and motor torque are constant the increased power output at the generator end tends to slow up the rotor of the generator and speed up the rotor of the motor and thus reestablish the original operating angle. This is an inherently stable operating position. The acceleration at either end varies directly as the excess of output over input and inversely as the inertia of the rotor. The actual rate of change, the resultant acceleration, of the angle is a resultant of the effects at the two ends. Both effects act in the same direction up to the angle corresponding to maximum power at the receiver (point of vertical tangency), *i. e.*, up to this point a small increment in angle produces retardation of the rotor at the generator or sending end and *acceleration* of the rotor of the motor but both effects tend to *decrease* the angle and to this extent act in the same direction. Slightly beyond this point an increment in angle produces retardation of the rotor at the receiving end. Both ends are now retardation. The resultant effect on the system depends upon which of the two retardations is the greater and these in turn are dependent upon the relative inertias of the two machines. For equal inertias and angles less than $\pi/2$, the generator will retard faster than the motor for positive increments in angle. When the angle is $\pi/2$ the retardation are equal but within the range of line angle, ψ to $\pi/2$, while both ends retard the generator retards sufficiently rapidly to maintain synchronism. The system as a whole will retard, reducing the frequency, but this will be taken care of by the automatic governors.

When the inertia of the generator is infinite the acceleration of the generator for any finite change in power is zero, so that the acceleration or retardation of the angle is determined entirely by that of the motor rotor. For positive increments in angle the acceleration of the motor rotor is positive up to the point where the line angle reaches ψ, beyond which it becomes negative. The stability of the system for this condition is coincident with the condition of maximum power at the receiver (d'' in Fig. 9) and the line angle is ψ, the argument of the complex number representing the admittance $\mathbf{Y}_{ab}$. When the inertia of the motor rotor is infinite the limit is determined for similar reasons by the condition of maximum power at the generator. This corresponds to a line angle of $\pi - \psi$, the operating points of which are indicated by c''' and d''' in Fig. 9. It is interesting to note in this connection that it is not only possible theoretically to operate beyond the point of maximum power of the receiving circle diagram such

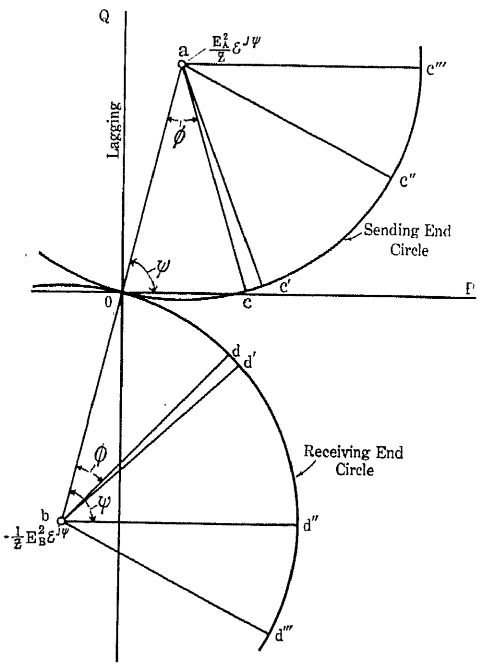

Fig. 9—Power Circle Diagram for the Simple Power System Shown in Fig. 8

as discussed for conditions when the inertia of the rotor of generator is other than infinite, but it is possible to operate beyond an angle of $\pi/2$, when the inertia at the receiving end is greater than that at the generator. While this is the condition usually met in practise it is not being advocated here to operate a system within that zone.

It follows from the above discussion that while the point of maximum power might be a stable operating point this method might give a result which would indicate that for the maximum angle at which it is possible to operate, the stability limit is lower than the maximum power, (*i. e.*, that the power at say d''' is lower than at d''). But to arrive at this operating point it is necessary with slowly increasing load to pass through the point of maximum power of the circle diagram. In such case the system reaches a maximum power limit before a stability limit. These ideas are merely being developed here to insure a clearer conception of static stability. Some of these operating conditions which are here shown to be stable were heretofore considered inherently unstable.

The natural period of a system varies with the magnitude of the oscillation and with the load. For small variations of angle the differential equation takes the form of equation (22). The natural period obtained from a solution of this equation is

$$T = \frac{2\,\pi}{\sqrt{-K}}$$

for K negative. The constant K is the slope of the

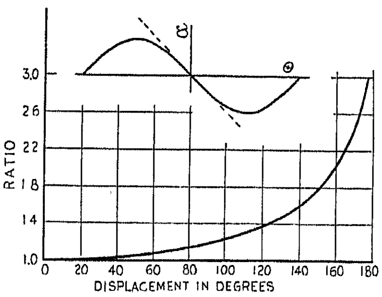

Fig. 10—Curve Showing Ratio Between Natural Period for Sinusoidal Variation of α and Linear Variation of α Plotted as a Function of Displacement

acceleration curve plotted as a function of the angle and is equal to $\dfrac{\alpha}{\theta}$

therefore

$$T = 2\,\pi\sqrt{\frac{\theta}{\alpha}} \qquad (31)$$

and is expressed in seconds when θ is expressed in electrical degrees and α in electrical degrees per second per second. As can be seen from equation (21). $\dfrac{\theta}{\alpha}$ increases with increasing angle, so that the natural period increases with angle or with load, reaching an infinitely large value at the static limit. Of course, all these considerations imply constant internal voltage. The increased natural period near the limit permits more time for the operation of automatic voltage regulators and exciters and indicates that the period near the limit is determined more by magnetic phenomena in the machines than by electromechanical phenomena.

In general, increasing the amplitude of the oscillation increases the natural period. For small oscillations the curve of α against θ can be considered linear, but for larger oscillations this is not justified. The correction, however, for amplitudes ordinarily met in practise is not great. For example, if the acceleration is a sinusoidal function of the angle the ratio of the actual period

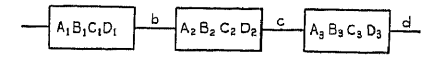

Fig. 11—General Case of Two Machines with Voltage Maintained at b and c

to that obtained by taking the slope for $\theta = 0$ is shown in Fig. 10.

Practical Calculation of Static Stability

In general, the voltage will be maintained constant at various points in the system and as the load varies the excitation must be changed either manually or by means of automatic voltage regulators to maintain this voltage. Because of this changing excitation and internal voltage it would be necessary by the method just described to calculate the angle and the internal voltage for each condition and then apply the criterion for stability to determine whether the system is stable or not. The following method for the calculation of maximum power does not require the knowledge of the internal voltage.

The most general case in which the problem can still be reduced to a single synchronous machine at each end is that shown in Fig. 11 in which the three rectangles represent general networks, $\mathbf{E}_a$ and $\mathbf{E}_d$ the internal voltages (to neutral) and b and c the points at which the voltages are maintained. The three general networks in series can be combined into one equivalent so that the following expression is obtained:

$$\mathbf{E}_a = \mathbf{A}_0\,\mathbf{E}_d + \mathbf{B}_0\,\mathbf{I}_d \qquad (32)$$

where, $\mathbf{A}_0$ and $\mathbf{B}_0$ are the general circuit constants for the three combined networks, $\mathbf{E}_a$ and $\mathbf{E}_d$ the star voltages at a and d respectively and $\mathbf{I}_d$ the current at d.

Transposing equation (32)

$$\mathbf{I}_d = \frac{1}{\mathbf{B}_0}\,\mathbf{E}_a - \frac{\mathbf{A}_0}{\mathbf{B}_0}\,\mathbf{E}_d \qquad (33)$$

from which it is seen that

$$\mathbf{Y}_{ab} = Y_{ab}\,\epsilon^{j\phi_1} = \frac{1}{\mathbf{B}_0} \qquad (34)$$

But

$$\mathbf{B}_0 = \mathbf{A}_1 (\mathbf{B}_3 \mathbf{A}_2 + \mathbf{D}_3 \mathbf{B}_2) + \mathbf{B}_1 (\mathbf{B}_3 \mathbf{C}_2 + \mathbf{D}_3 \mathbf{D}_2) \quad (35)$$

so that ϕ_1 is the negative of the argument of the complex number $\mathbf{B}_0$. The limiting angle, ϕ_0, is related to ϕ_1 by the relation expressed by equation (**24**) and is dependent upon the relative inertias.

Having obtained the maximum overall angle corresponding to the limit of stability, the actual value of power delivered can be determined by the following graphical means. From a knowledge of $\mathbf{A}_2$, $\mathbf{B}_2$, $\mathbf{C}_2$, $\mathbf{D}_2$ and the voltages at b and c, the sending and receiving-end power circle diagrams for the middle section can be drawn as shown by the heavy lines in Fig. 12. For any angle β between the voltages at b and c the power

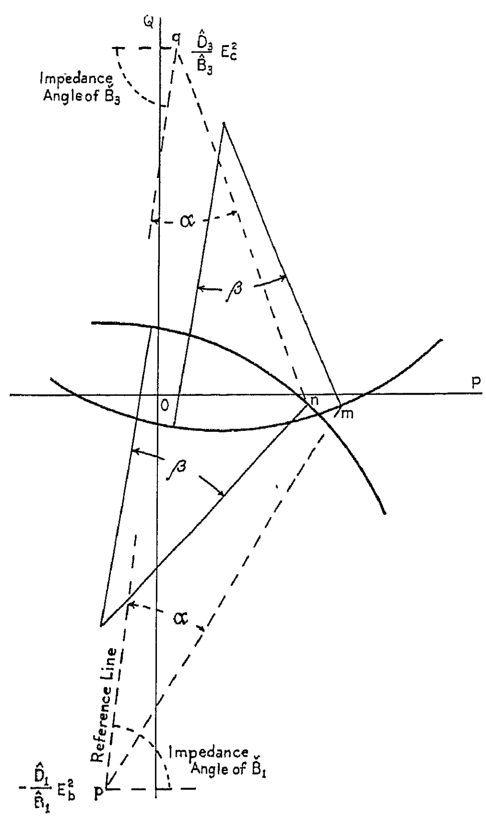

FIG. 12—POWER CIRCLE DIAGRAMS FOR TWO-MACHINE PROBLEMS

flow at these points is indicated by the points m and n. Every point such as m on the supply circle must also represent a point on the receiving circle for the first section. This latter circle is represented by the expression

$$P_b + j\, Q_b = \frac{1}{\mathfrak{B}_1} E_A\, E_B\, \epsilon^{-j\alpha} - \frac{\mathfrak{A}_1}{\mathfrak{B}_1} E_B^2$$

The center of this circle is located at $-\dfrac{\mathfrak{A}_1}{\mathfrak{B}_1} E_B^2$.

It will be noted that all of these quantities are known and can be plotted as shown by the point p. Now while the value of the voltage $\mathbf{E}_A$ is unknown (and incidentally will not be necessary to determine) the reference vector from which the angle α is measured can be drawn making an angle with the horizontal equal to that of $\dfrac{1}{\mathfrak{B}_1}$ which angle is the same as the angle of $\mathbf{B}_1$, *i. e.*, $\tan^{-1} \dfrac{b_1}{a_1}$ where $\mathbf{B}_1 = a_1 + j\, b_1$. As stated previously, the point m must lie on the receiving power circle diagram for the first section, and therefore, the angle α between $p\, m$ and the reference line indicates the angle between the voltages at a and b for the power transmitted at c corresponding to point n.

A similar construction applies to the receiving-end network. The power at c into this network is expressed

$$P_c + j\, Q_c = \frac{\mathfrak{D}_3}{\mathfrak{B}_3} E_C^2 - \frac{1}{\mathfrak{B}_3} E_C\, E_D\, \epsilon^{+j\gamma}$$

The center of the circle q is determined by $\dfrac{\mathfrak{D}_3}{\mathfrak{B}_3} E_C^2$ and the reference line makes an angle with the horizontal equal to that of $-\dfrac{1}{\mathfrak{B}_3}$, *i. e.*, $\tan^{-1} \dfrac{b_3}{a_3}$ where $\mathfrak{B}_3 = a_3 + j\, b_3$.

The angle γ between $n\, q$ and the reference line indicates the angle between the voltages at c and d. Therefore, $\alpha + \beta + \gamma$ gives the total angle between the voltages at a and d for the power conditions at c corresponding to the point n. After a few trials the point n can be determined for which $\alpha + \beta + \gamma = \phi_0$. This gives the amount of power that can be transmitted at c for the maximum operating angle ϕ_0. This is the maximum angle at which the system is still stable. The maximum power may sometimes occur for a smaller angle.

The general method can best be illustrated by means of a solution for a particular case. The example chosen is the determination of the static power limit for a 270,000-kv-a. generator, transformers, a 250-mile line and a 170,000-kv-a. synchronous motor. The voltage at the generator and motor terminals will be maintained at an equivalent of 220 kv. by hand regulation. The constants of the line and machines are as follows:

Line Constants:

Length of line	= 250 miles
Frequency	= 60 cycles
Resistance per mile	= 0.151 ohms
Reactance per mile	= 0.813 ohms
Admittance per mile	= 5.22 micro-mhos
Conductance per mile	= 0

Step-up Transformers:

270,000 kv-a. total. 12% Reactance
13,200—220,000 volts.

Step-down Transformers:

240,000 kv-a. total. 12% Reactance
210,000—13,200 volts

Generators:

270,000 kv-a. total
0.9 power-factor, 13,200 volts
100% Synchronous impedance.

Synchronous Motor:

170,000 kv-a.
85% Synchronous impedance.

The combined constants for transformers and line are:

$$\mathbf{A}_2 = 0.8431 + j\,0.0279$$
$$\mathbf{B}_2 = 39.6 + j\,232.1$$
$$\mathbf{C}_2 = (0.0104 + j\,1.248)\,10^{-3}$$
$$\mathbf{D}_2 = 0.8428 + j\,0.0280$$

These constants are sufficient to permit the construction of the sending and receiving power circle

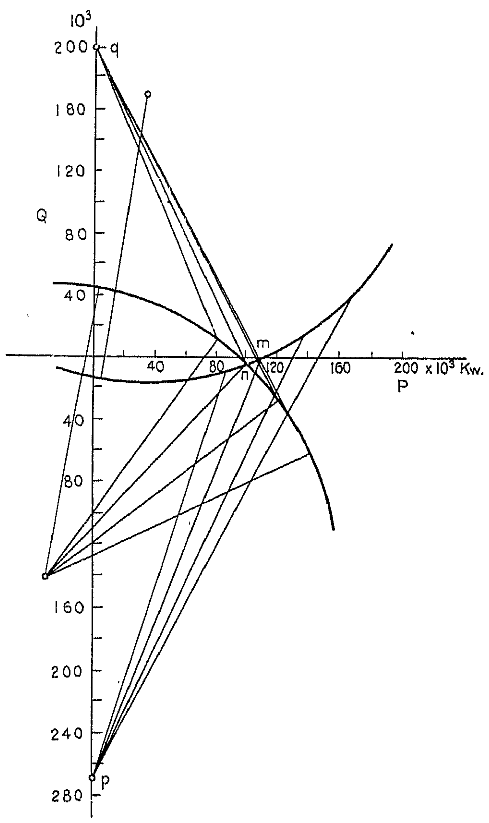

FIG. 13—CIRCLE DIAGRAM FOR ILLUSTRATION OF TWO-MACHINE PROBLEM

diagrams in the ordinary way. These are indicated by the full lines in Fig. 13.

The center of the receiving circles for network 1 is located at $-\dfrac{\mathfrak{A}_1}{\mathfrak{B}_1} E_B{}^2$. Since this network contains only the generator reactance

$$\mathbf{A}_1 = 1.0 + j\,0$$
$$\mathbf{B}_1 = 0 + j\,X_1$$

and

$$\frac{\mathfrak{A}_1}{\mathfrak{B}_1} = \frac{1}{-j\,X_1}$$

$$-\frac{\mathfrak{A}_1}{\mathfrak{B}_1} E_B{}^2 = -j\,\frac{E_B{}^2}{X_1}$$

$$= -j\,\frac{220 \times 220{,}000}{179.2} = -j\,270{,}000 \text{ kv-a.}$$

Incidentally, this is equal to the sustained short circuit

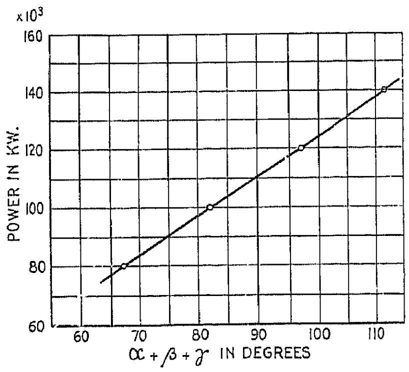

FIG. 14—POWER-ANGLE DIAGRAM FOR SYSTEM OF FIGS. 11 AND 13

kv-a. at the point b. The center of the generator circle is indicated by the letter p on Fig. 13. The reference line coincides with the axis of reactive power.

The center of the sending circles for network 3 is obtained in a similar manner.

$$\mathbf{D}_3 = 1.0$$
$$\mathbf{B}_3 = 0 + j\,X_3$$
$$\frac{\mathfrak{D}_3}{\mathfrak{B}_3} = \frac{1}{-j\,X_3}$$

The center is located at

$$\frac{\mathfrak{D}_3}{\mathfrak{B}_3} E_C{}^2 = \frac{E_C{}^2}{-j\,X_3}$$

$$= j\,\frac{200 \times 200{,}000}{200} = j\,200{,}000$$

This point is plotted at q, the reference line being the axis of reactive power.

Now give β an arbitrary value, say 34 degrees, and determine m and n for this value. Draw $m\,p$ and $n\,q$ and measure α and γ.

$$\alpha = 22.3 \text{ degrees}$$
$$\gamma = 26.0 \text{ degrees}$$
$$\alpha + \beta + \gamma = 82.3 \text{ degrees}$$

The total angle between internal voltages is then equal to 82.3 degrees for 100,000 kw. transmitted at the

receiving end. Choose a different value of β and repeat. By this means the curve in Fig. 14 can be obtained.

The final step consists in determining the limiting angle. If the inertias of the two machines are equal the limiting angle is 90 deg. and the power corresponding to this angle can be read directly from the curve and is found to be 111,000 kw. When $W_a \neq W_b$ it is necessary to calculate ϕ_0 from equation (**24**). Substituting in equation (**35**) $\mathbf{B}_0$ is found equal to

$$\mathbf{B}_0 = 28.6 + j\,506.7$$

and

$$\phi_1 = -\tan^{-1}\frac{506.7}{28.6} = -86.7 \text{ degrees.}$$

From equation (**24**)

$$\phi_0 = \tan^{-1}\frac{W_b + W_a}{W_b - W_a}\tan\phi_1$$

Using this formula ϕ_0, can be calculated for any combination of inertias.

If $W_a = \infty$

$\phi_0 = 86.7$ degrees.

and the power limit is 106,500 kw.

If $W_b = \infty$

$\phi_0 = 180 - 86.7 = 93.3$ degrees.

and the power limit is 116,000 kw.

For other values of inertia, the power limit will be somewhere between these two limits. For example, if the

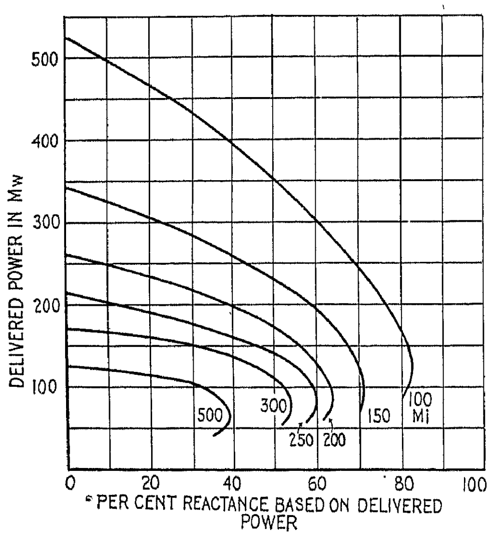

Fig. 15—Stability Limit of 220-Kv. Systems Having Identical Generators and Motors

3-phase, 60-cycle, 795,000-cir. mils aluminum condenser, steel reinforced 29-ft. equivalent spacing

stored energy at the receiving end is twice that at the sending end

$$\phi_0 = -\tan^{-1}\frac{3}{1}\cdot\frac{506.7}{28.6} = 92.2 \text{ degrees.}$$

and the power limit is 113,000 kw.

For those problems involving low inertia hydroelectric generating stations feeding a load through long lines the stored energy at the receiving end is usually larger than at the sending end so that the limiting angle is usually larger than 90 degrees. It is, therefore, usually found that using 90 degrees as the limiting angle

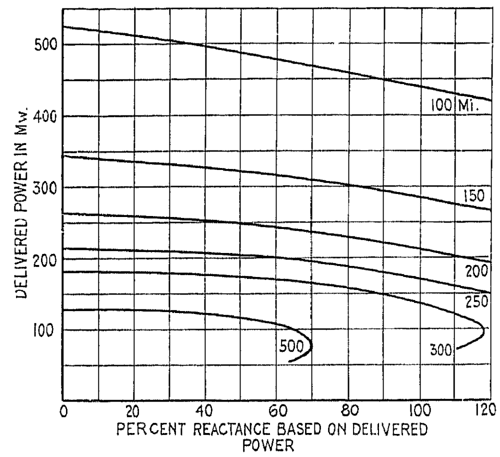

Fig. 16—Stability Limit of 220-Kv. System with Infinite Bus at Receiver

3-phase, 60-cycle, 795,000-cir. mils aluminum condenser, steel reinforced, 29-ft. equivalent spacing

gives limits which are slightly low. Some problems arise in which the curve of Fig. 14 reaches a maximum and begins to droop before the limiting angle is reached. The cases of this nature which have been examined were cases in which considerable power was being supplied by local generators and the line itself was really operating at an angle beyond 90 degrees so that as far as the line itself is concerned, with increasing line angle, the power limit of the line is reached before the stability limit. In such a case the system would never be operated at or near the angle corresponding to the actual stability limit; the operating angle of the line corresponding to this condition represents an impractical condition.

Stability Limits of 220- and 110-Kv. Transmission Systems

The methods which have just been described have been applied to the calculation of the stability limits of 60-cycle, 220-kv. transmission systems of various lengths. Fig. 15 shows the stability limits for systems with generator and step-up transformer at one end and step-down transformer and synchronous motor at the other end, the generator and motor being identical in electrical and mechanical characteristics, and the voltage being maintained at 220 kv. on the high voltage side of the transformers. Fig. 16 shows the stability limits for the same lines fed into an infinite bus at the receiving end, that is, the voltage at the receiving end is maintained constant at 220 kv. and the inertia of the apparatus at the receiving end is assumed to be in-

finitely large. In both cases the generator reactance in per cent was based upon the delivered power.

The curves of Figs. 15 and 16 may be used in estimating the static stability of systems by considering how the particular system approaches either of these conditions upon which the calculations were based. These curves will also be found useful in comparing the relative effects of generator reactance and length of line upon the stability limits. It should be borne in mind that these results do not indicate the value at which it is desirable to operate the system but rather that they represent

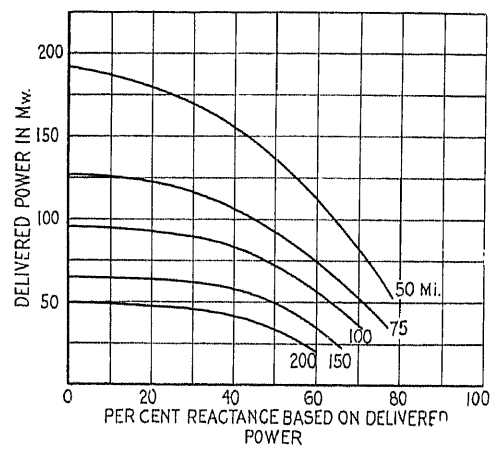

FIG. 17—STABILITY LIMITS OF 110-KV. SYSTEMS HAVING IDENTICAL GENERATORS AND MOTORS

3-phase, 60-cycle, 4-0 copper, 13-ft. equivalent spacing

the very limit of power which can be transmitted and that the system should be so designed that even during emergency conditions these values should not be approached.

Figs. 17 and 18 show similar static power limits for a typical single-circuit, 110-kv. system. The assumptions as to load were identical.

THREE-MACHINE PROBLEM

A large percentage of the problems met in practise can be reduced to the equivalent of a two generator problem—a synchronous generator at the sending end and a synchronous motor or generator supplying a local load at the receiving end. There exist, however, a large number of problems which can not be so simplified. A particular case, and one with which this paper is largely concerned is that of ascertaining the effect of an intermediate condenser station in improving the stability limit. This type of problem has been termed "the three-machine problem," because, in the general case it involves three sources of synchronous e. m. fs. The solution of this problem immediately permits of the solution of a large number of problems previously considered too involved or complicated. The number that may be so solved are fewer than those that may be solved by the two-machine problem. There still remain a large number of problems which lie beyond the scope of either the two- or three-machine problem. The solution of some of these, inherently involve the addition of another source of synchronous e. m. f., requiring the solution of the "four-machine problem." A particular case of this type and one with which this paper is concerned, is that of a transmission system with two intermediate condenser stations. The solution of the three-machine problem will now be discussed.

As shown previously, the general circuit conditions for the three-machine problem in which loads are represented by impedances, are completely defined by the following equations:

$$\mathbf{I}_a = \mathbf{Y}_{aa}\,\mathbf{E}_a - \mathbf{Y}_{ab}\,\mathbf{E}_b - \mathbf{Y}_{ac}\,\mathbf{E}_c$$
$$\mathbf{I}_b = -\,\mathbf{Y}_{ba}\,\mathbf{E}_a + \mathbf{Y}_{bb}\,\mathbf{E}_b - \mathbf{Y}_{bc}\,\mathbf{E}_c$$
$$\mathbf{I}_c = -\,\mathbf{Y}_{ca}\,\mathbf{E}_a - \mathbf{Y}_{cb}\,\mathbf{E}_b + \mathbf{Y}_{cc}\,\mathbf{E}_c$$

As shown in Appendix I, the conditions which must be fulfilled at all times so that the system remains in synchronism are,

$$\left.\begin{array}{l} a > 0 \\ b > 0 \\ a^2 > 4\,b \end{array}\right\} \qquad (36)$$

in which a and b are functions of the network constants, the inertia of the machines, the internal voltages, and the angles between the internal voltages. These functions are derived in the appendix.

The above relations supply a test which can always

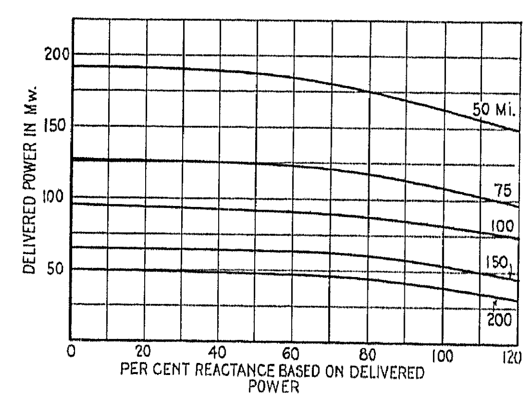

FIG. 18—STABILITY LIMIT OF 110-KV. SYSTEMS WITH INFINITE BUS AT RECEIVER

3-phase, 60-cycle, 4-0 copper, 13-ft. equivalent spacing

be applied for the stability of a three-machine system. This type of problem differs somewhat from a two-machine problem because of the larger number of possible solutions. Given the inertias and the phase angle of the $\mathbf{Y}_{ab}$ admittance in a two-machine problem, the maximum operating angle is completely determined, but in a three-machine problem the maximum operating angle between any two voltages is dependent upon the conditions at the third. The line of attack shall be to determine the phase position and magnitude of the internal voltages and then to apply the test for stability. In general, a three-machine problem possesses five

degrees of freedom; after knowing the circuit constants it is necessary to know five additional quantities before the distribution of real and reactive power can be determined. These quantities might be three voltages and the angles between them or they might be three voltages, power at a point and the angle between two voltages. The intermediate condenser station problem may be cited as a particular example. Suppose the voltage be maintained constant at the terminals of the generator at the sending end, at the terminals of the condenser, and at the terminals of a generator at the receiving end. In addition suppose the power input into the system by the condenser will be zero. Under these conditions, one additional quantity permits of a solution of the operating condition. If the power supplied by the receiving end generator be fixed, the reactive power of that machine is also fixed; the real and reactive power of the sending end generator, the reactive power of the condenser, the internal voltages of all three machines and their relative phase angles, all, can be determined. Having fixed the last permissible variable and applied the test for stability, another value of the variable may be chosen and this process continued until the test shows instability; that is, until one of the conditions for stability fails.

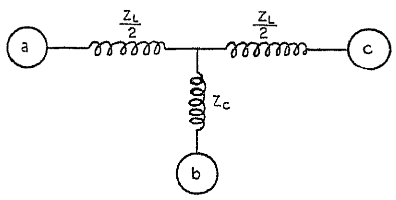

FIG. 19—CIRCUIT FOR SYMMETRICAL INTERMEDIATE CONDENSER CASE

The calculations of a number of practical cases including an intermediate condenser indicate that the relation $b > 0$ is the condition which usually fails first, that is, becomes the limiting condition. This is supported by the analysis of a number of simplified cases. One of these is the case of a generator, motor, and an intermediate condenser of zero impedance connected by reactive lines in which both the resistance in the lines and machines are neglected. It is interesting to note in connection with this particular case that the condition which must hold for the system to remain in a stable condition is dependent only upon the angle between the voltages and is independent of the inertias, the reactance of the circuit, the magnitude of the voltages and the location of the condenser. It will be shown in the next section that this condition also holds for the case in which the condenser impedance is finite and the system is symmetrical about the condenser.

Accepting this as the limiting condition, the following relation regarding inertias is obtained. The general form for b is

$$b = (A-B-F)\ (C-D+E)+(D-F)\ (A-E) > 0 \quad (37)$$

Each of the terms denoted by A, B, C, etc., possess one value of inertia. After expanding, the expression b can be arranged in three groups having $\frac{1}{W_a\,W_b}$, $\frac{1}{W_b\,W_c}$ and $\frac{1}{W_c\,W_a}$, respectively, for coefficients.

If the stored energy of all the machines is equal, the three coefficients are equal so that the limiting conditions become independent of inertia or if any one has an extremely large inertia, in the limit, say infinitely large, the power limit of the system is independent of the inertias of the other machines. Similarly, if the inertia of one machine is zero and the other two equal, the limit is independent of the values of the other two machines.

INTERMEDIATE CONDENSER STATION · PURE REACTANCE LINES

An example of the three-machine problem which is sufficiently simple to permit of mathematical analysis to determine which of the stability conditions will be controlling and from which important practical conclusions regarding static stability may be drawn is the case of a transmission system in which the resistance and charging current are neglected, with a condenser station located midway in the line. Assume a synchronous motor load whose characteristics are identical to those of the generator. Let a be the generator, b the condenser, and c the motor, (see Fig. 19) and

$\mathbf{E}_A$ = Internal voltage of generator
$\mathbf{E}_B$ = Internal voltage of condenser
$\mathbf{E}_C$ = Internal voltage of motor
$\mathbf{E}_t$ = Terminal voltage of condenser
$\mathbf{Y}_{ab}$ = Admittance between E_A and E_B
$\mathbf{Y}_{bc}$ = Admittance between E_B and E_C
$\mathbf{Y}_{ac}$ = Admittance between E_C and E_A
ϕ_x = Angular difference in rotor positions between a and b, and b and c.
$\mathbf{Z}_L$ = Line plus apparatus impedance between E_a and E_c
$\mathbf{Z}_C$ = Impedance of condenser branch, *i. e.*, condenser and transformer.

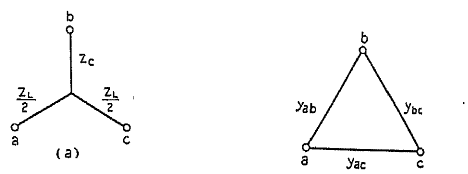

FIG. 20—STAR-DELTA TRANSFORMATION

By means of a simple delta-star conversion the network of Fig. 20A may be transformed into that of Fig. 20B in which

$$Y_{ab} = \frac{2}{Z_L + 4 Z_C}$$

$$Y_{ac} = \frac{4 Z_C}{Z_L (Z_L + 4 Z_C)}$$

By assumption

$$\phi_1 = \phi_2 = \phi_3 = -\frac{\pi}{2}$$

$$W_c = W_a$$
$$E_C = E_A$$

The constants for the criteria of stability as developed in Appendix I will reduce to the following:

$$A = \frac{Y_{ab} E_A E_B}{W_b} \sin\left(\phi_x - \frac{\pi}{2}\right) = -\frac{Y_{ab} E_A E_B}{W_b} \cos \phi_x$$

$$B = \frac{Y_{ab} E_A E_B}{W_a} \sin\left(\phi_x + \frac{\pi}{2}\right) = \frac{Y_{ab} E_A E_B}{W_a} \cos \phi_x$$

$$C = \frac{Y_{ab} E_A E_B}{W_a} \sin\left(\phi_x - \frac{\pi}{2}\right)$$

$$= -\frac{Y_{ab} E_A E_B}{W_a} \cos \phi_x = -B$$

$$D = \frac{Y_{ab} E_A E_B}{W_b} \sin\left(\phi_x + \frac{\pi}{2}\right)$$

$$= \frac{Y_{ab} E_A E_B}{W_b} \cos \phi_x = -A$$

$$E = \frac{Y_{ac} E_A^2}{W_a} \sin\left(2\phi_x - \frac{\pi}{2}\right) = -\frac{Y_{ac} E_A^2}{W_a} \cos 2\phi_x$$

$$F = \frac{Y_{ac} E_A^2}{W_a} \sin\left(2\phi_x + \frac{\pi}{2}\right)$$

$$= \frac{Y_{ac} E_A^2}{W_a} \cos 2\phi_x = -E$$

The criteria for stability may now be determined

$$\underline{b > 0}$$

$$b = K_1 K_5 - K_2 K_4$$
$$= (A + E - B)^2 - (-A + E)^2$$
$$= \frac{Y_{ab}^2 E_A^2 E_B^2}{W_a} \left[\frac{2}{W_b} + \frac{1}{W_a}\right] \cos \phi_x$$
$$\cdot \left[\frac{2 Y_{ac} E_A}{Y_{ab} E_B} \cos 2\phi_x + \cos \phi_x\right]$$
$$= \frac{2 Y_{ac} Y_{ab} E_A^3 E_B}{W_a} \left[\frac{2}{W_b} + \frac{1}{W_a}\right] \cos \phi_x$$
$$\left[\cos 2\phi_x + \frac{Z_L E_B}{4 Z_C E_A} \cos \phi_x\right] >$$

$$\underline{a > 0}$$

$$a = -(K_1 + K_5)$$
$$= 2(-A + B - E)$$
$$= \frac{2 Y_{ac} Y_{ab} E_A^2}{W_a} \left[\cos 2\phi_x + \frac{1}{2} \frac{Z_L}{Z_C} \frac{E_B}{E_A} \left(1 + \frac{W_a}{W_b}\right) \cos \phi_x\right] > 0$$

$$\underline{a^2 - 4b > 0}$$

$$a^2 - 4b = (K_1 + K_5)^2 - 4(K_1 K_5 - K_2 K_4)$$
$$= (K_1 - K_5)^2 + 4 K_2 K_4$$
$$= (K_1 - K_5)^2 + (-A + E)^2 > 0$$

Of the three conditions, the last is always fulfilled and may be dismissed. The other two conditions contain terms of the form

$$\cos 2\phi_x + M \cos \phi_x \tag{38}$$

in which M is the positive coefficient of $\cos \phi_x$. Examination of functions a and b indicate that the conditions fail when either $\cos \phi_x$ of function b or one of the terms of form (**38**) in either function a or b equals zero. The limiting condition is that one for which this equality is true for the smallest angle. The term of the form (**38**) equals zero, depending upon the value of M, between $\pi/4 < \phi_x < \pi/2$ but $\cos \phi_x$ equals zero only at $\pi/2$. The discussion, therefore, narrows down to an examination of the two terms in a and b of the above form (**38**). This term may be written

$$2 \cos^2 \phi_x + M \cos \phi_x - 1 = 0 \tag{39}$$

$$\cos \phi_x = \frac{-M \pm \sqrt{M^2 + 8}}{4} \tag{40}$$

Examination of this equation shows that the smaller value of ϕ_x will be obtained for the smaller value of M. Since the M constant for the b condition is always smaller than that for the a condition, in the ratio $\frac{1}{2\left(1 + \frac{W_a}{W_b}\right)}$, the b condition is always the limiting one. The value of M to be used is

$$M = \frac{Z_L}{4 Z_C} \frac{E_B}{E_A} \tag{41}$$

The direct application of this relation requires a knowledge of the internal voltage E_B, of the condenser which is not usually known. The usual practise is to regulate for constant voltage at the terminals of the machine or by means of a compensator on the high side of the condenser transformers. Using the latter assumption it can be shown by means of a power circle diagram that the kv-a. supplied by the condenser is

$$Q = \frac{4\,E_t^2}{Z_L} - \frac{4\,E_t\,E_A}{Z_L}\cos\phi_x \qquad (42)$$

The internal voltage of the condenser is then

$$E_B = E_t + Z_C\,\frac{Q}{E_t}$$

$$= E_t + \frac{4\,Z_C}{Z}\,E_t - \frac{4\,Z_C}{Z_L}\,E_A\cos\phi_x$$

or multiplying by $\dfrac{Z_L}{4\,Z_C\,E_A}$

$$\frac{Z_L}{4\,Z_C}\,\frac{E_B}{E_A} = M = \frac{1}{4}\left(\frac{Z_L}{Z_C} + 4\right)\frac{E_t}{E_A} - \cos\phi_x \qquad (43)$$

Substituting the values of M from equation (43) in

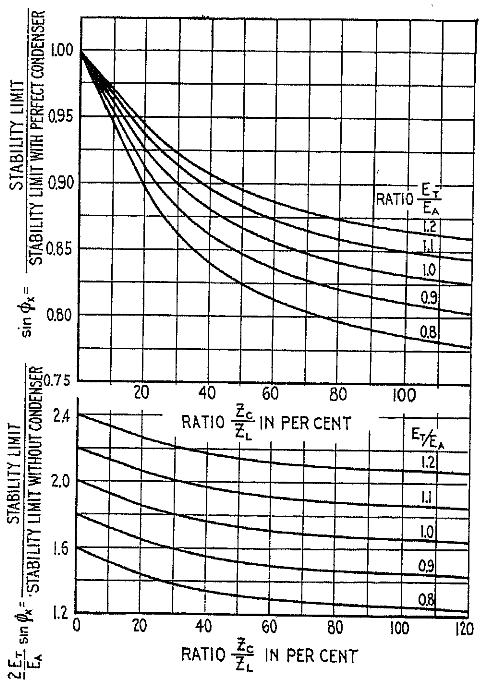

FIG. 21—EFFECT OF INTERMEDIATE CONDENSER ON STABILITY LIMIT

equation (39) permits a determination of $\cos\phi_x$ from which $\sin\phi_x$ may be plotted as a function of $\dfrac{Z_C}{Z_L}$ for the different values of $\dfrac{E_t}{E_A}$ as shown in Fig. 21. The quantity $\sin\phi_x$ gives a direct measure of the improvement in stability limit obtainable by virtue of the condenser. The power at C is

$$P_c = \frac{2\,E_t\,E_A}{Z_L}\sin\phi_x \qquad (44)$$

With a condenser of zero impedance the power limit is $2\,E_t\,E_A/Z_L$, so that the ratio of the power that can be transmitted with a finite condenser to that which can be transmitted with a condenser of zero impedance is $\sin\phi_x$.

The power limit of the line without an intermediate condenser station is E_A^2/Z_L. The improvement achieved by the intermediate condenser is then $2\,E_t\sin\phi_x/E_A$. This quantity is also plotted in Fig. 21.

In reviewing the properties of a system with an intermediate condenser it will be noted first that the stability limit for the symmetrical case is independent of the inertias. In addition it will be observed that a given condenser will show to better advantage on a long line than on a short line or expressed differently, a short line requires a condenser of lower impedance than a longer line to produce the same improvement.

FOUR-MACHINE PROBLEM

The circuit conditions for the "four-machine" problem referred to previously are completely defined by the following equations:

$$\left.\begin{aligned}
\mathbf{I}_a &= \mathbf{Y}_{aa}\,\mathbf{E}_a - \mathbf{Y}_{ab}\,\mathbf{E}_b - \mathbf{Y}_{ac}\,\mathbf{E}_c - \mathbf{Y}_{ad}\,\mathbf{E}_d \\
\mathbf{I}_b &= -\,\mathbf{Y}_{ba}\,\mathbf{E}_a + \mathbf{Y}_{bb}\,\mathbf{E}_b - \mathbf{Y}_{bc}\,\mathbf{E}_c - \mathbf{Y}_{bd}\,\mathbf{E}_d \\
\mathbf{I}_c &= -\,\mathbf{Y}_{ca}\,\mathbf{E}_a - \mathbf{Y}_{cb}\,\mathbf{E}_b + \mathbf{Y}_{cc}\,\mathbf{E}_c - \mathbf{Y}_{cd}\,\mathbf{E}_d \\
\mathbf{I}_d &= -\,\mathbf{Y}_{da}\,\mathbf{E}_a - \mathbf{Y}_{db}\,\mathbf{E}_b - \mathbf{Y}_{dc}\,\mathbf{E}_c + \mathbf{Y}_{dd}\,\mathbf{E}_d
\end{aligned}\right\} \qquad (45)$$

in which the $\mathbf{I}_a$, $\mathbf{I}_b$, $\mathbf{I}_c$, and $\mathbf{I}_d$ are line currents and $\mathbf{E}_a$, $\mathbf{E}_b$, $\mathbf{E}_c$, and $\mathbf{E}_d$ the voltages to neutral. As shown in the Appendix I the necessary conditions which must be fulfilled so that the system remains in synchronism are

$$\left.\begin{aligned}
c &> 0 \\
b &> 0 \\
a\,b - 9\,c &> 0 \\
\Delta - b &> 0 \\
a^2 - 3\,b &> 0
\end{aligned}\right\} \qquad (46)$$

in which a, b, c, and Δ, defined in the Appendix, are functions of the circuit constants, system voltages, and inertias of the machines.

All of these conditions must be fulfilled simultaneously. The failure of any one is sufficient proof of instability. In problems of a given type one of them will be found to fail before the others and after establishing the particular one, it will be necessary to consider only this one condition.

The problem involving two intermediate condensers with synchronous machines at each end of the line has been chosen for discussion because of its important bearing on long distance power transmission. The condensers were assumed to have zero impedance and the resistance and charging current were neglected. Theoretical analysis of this case indicated that the c condition was the limiting one. It further showed that the stability limit occurred when the angle between any two adjacent machine voltages became equal to $\pi/2$. This conclusion is independent of the inertia of the machines, of the magnitude of machine voltages and of the location of the condensers.

Calculations of stability limits of practical cases, the

results of which will be given later, also indicated that the c condition is controlling.

Assuming then that this condition will be limiting for all practical cases involving two intermediate condenser stations, interesting relations may be derived.

$$c = K_1 K_6 K_8 + K_2 K_4 K_9 + K_3 K_5 K_7 - K_1 K_5 K_9 - K_2 K_6 K_7 K_3 K_4 K_8 > 0 \qquad (47)$$

Since each of the K's contains only one inertia term and c is composed of groups of three, the terms can be expanded into four groups having for the coefficients the terms $\frac{1}{W_a W_b W_c}$, $\frac{1}{W_a W_b W_d}$, $\frac{1}{W_b W_c W_d}$, $\frac{1}{W_a W_c W_d}$, respectively. If one of the inertias be infinitely large three of the groups become zero so that the limit becomes independent of the inertias of the other machines. Other combinations for which the limit is independent of the inertias of the machines are:

1. All equal
2. One zero and other three equal
3. Two zero and other two equal.

Stability Limits with Intermediate Condenser Stations

An important application of the theory and methods developed is for the determination of the stability limits of transmission systems with synchronous condenser stations located at intermediate points along the transmission line. This is of particular interest at this time because of its bearing on long distance power transmission. The problems involving one and two intermediate synchronous condensers are special cases of the three- and four-machine problems in which power input and output of the intermediate machines, except for losses, are made equal to zero.

Three general questions arise as to the intermediate condenser station under static conditions, namely, location, voltages to be maintained and condenser characteristics.

Location of one intermediate condenser for a symmetrical system is clearly at the midpoint of the series impedance of the system regardless of the characteristics of the condenser station itself. With two intermediate condensers the answer is less simple. With zero impedance on a symmetrical system the condensers should be located so as to divide the system into three equal sections. With finite condenser impedance the middle section should be of relatively less impedance than the end sections. With finite impedance condensers the variations from the best theoretical location will have relatively little effect on the stability limit, consequently power system layout need not be handicapped by a requirement to obtain the theoretically best location of condensers at intermediate points.

In regard to the voltages to be maintained there is, undoubtedly, an advantage in maintaining them at as high values as permissible without reduction of voltages at other points. Practically, this means that the voltage at condenser stations should be maintained on the high voltage line at the highest permissible value.

With respect to the characteristics of a condenser this subject can best be discussed by showing the results of calculations. The first case considered is that of one intermediate condenser located between the sending and receiving ends of 220-kv. transmission systems of various lengths. The sum of generator and transformer reactances was assumed in every case to be 12.5 per cent on 100,000 kv-a., and their resistances were neglected. The voltage was assumed to be maintained at 220 kv. on the high-voltage side of the transformers at the generating, receiving, and intermediate condenser stations. The best simple approximation of most of the receiving systems met in practise is the assumption of infinite capacity of the receiving end; that is, zero

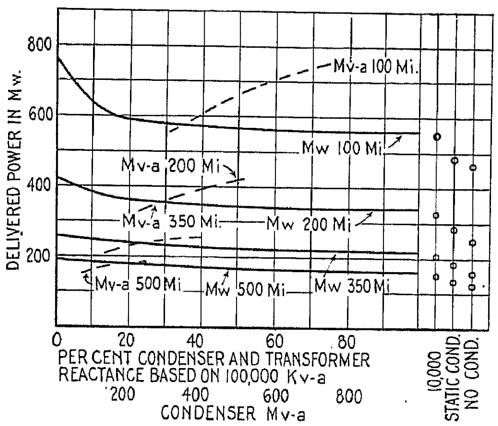

Fig. 22—Stability Limit of 220-Kv. Lines of Various Lengths with One Intermediate Condenser Station

3-phase, 60-cycle, 795,000-cir. mils aluminum condenser, steel reinforced, 29-ft. equivalent spacing, generator and transformer reactance, 12.5 per cent based on 100,000 kv-a. infinite bus and inertia at receiver

machine impedance and infinite inertia. It was shown in the discussion of the three-machine problem that when the inertia of one machine was infinite, static stability limits were independent of the inertia of the other two machines. In Fig. 22 are shown the results of calculations of the stability limits of transmission lines of various lengths plotted as a function of the reactance of the condenser and its transformer. In addition, the condenser capacity required at the stability limit is shown by the dotted lines. In estimating the stability limits of particular systems it will be found convenient to make use of the curves showing condenser capacity required at the stability limit in order to convert the impedance base from 100,000 kv-a. to the base corresponding to the capacity considered. At the right of Fig. 22 the following data are plotted:

1. The stability limit of systems with condensers having the extremely high impedance of 10,000 per cent.

This corresponds to the condition of an essentially constant current condenser.

2. The stability limit of systems with variable capacity static condensers located at the same points as synchronous condensers. In this case the condenser capacity was made variable to maintain the transmission voltage constant at 220 kv.

3. The static stability limit of the line alone, that is, without any apparatus at the intermediate points.

In Fig. 23 the same data are plotted in a different manner to show the per cent increase in stability limit as a function of the length of the line. These curves are interesting because they indicate the relatively small improvement obtainable by means of variable static condensers. The difference in stability limit may be explained in a qualitative manner as being due to the variation of the reactive kv-a. with voltage for the different types of apparatus as illustrated in Fig. 24. It will be observed that the greater the increase in leading kv-a., the greater will be the stability limit.

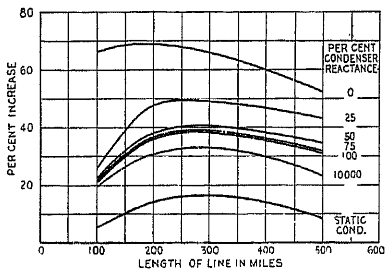

Fig. 23—Increase in Stability Limits of 220-Kv. Lines of Various Lengths Obtainable by One Intermediate Condenser Station

3-phase, 60-cycle, 795,000-cir. mils aluminum condenser, steel reinforced, 29-ft. equivalent spacing, generator and transformer reactance 12.5 per cent based on 100,000 kv-a. Infinite bus and inertia at receiver

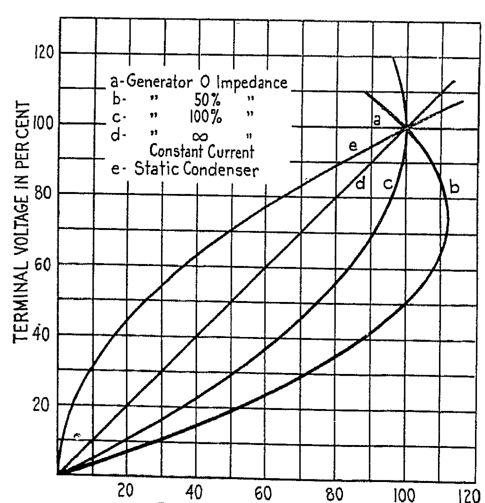

Fig. 24—Variation of Kv-a. with Voltage of Synchronous Condensers of Various Impedance and also Static Condensers

Similar calculations were made for the 350-mile line with two intermediate condenser stations instead of one with the results shown in Fig. 25. The increase in power limits obtainable by the installation of one and two condensers is shown in Fig. 26 which is plotted in

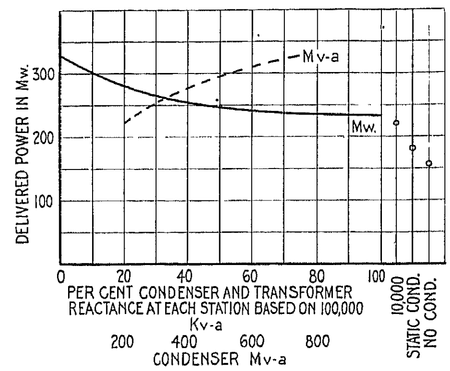

Fig. 25—Variation of Stability Limit of a 350-Mi., 220-Kv. Line with Condenser Impedance

350-mi. line, 220-kv., 3-phase, 60-cycle, 795,000-cir. mils aluminum condenser, steel reinforced, 29-ft. equivalent spacing, generator and transformer reactance 12.5 per cent based on 100,000 kv-a. Infinite bus and inertia at receiver

the per cent increase in stability limit as a function of the condenser impedance. It will be observed that the curves which are plotted for the same total condenser capacity show that relatively less improvement is obtained by using the second condenser station.

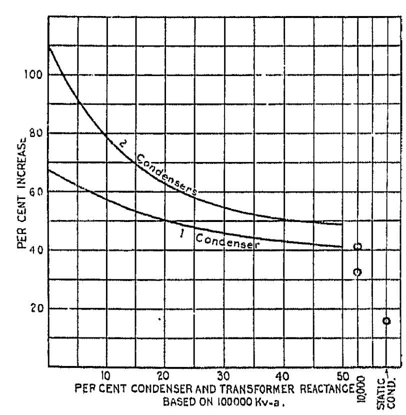

Fig. 26—Increase in Stability Limit Obtainable with One and Two Intermediate Condenser Stations

The curve assumes identical condenser characteristics for both cases, the total installed capacity being divided for the two-condenser case. 350-mi. line, 220-kv., 3-phase, 60-cycle, 795,000-cir. mils aluminum condenser, steel reinforced, 29 ft. equivalent spacing, generator and transformer reactance 12.5 per cent based on 100,000 kv-a. Infinite bus and inertia at receiver

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Summary

The principal features of this paper may be summarized as follows:

For static stability calculations, power systems may be represented by a network with constant impedance and admittance branches with as many terminals as the number of synchronous machines requiring individual consideration. This method is justified because, as developed in the paper, loads may be represented by the equivalent constant admittances and synchronous machines may be replaced by their equivalent impedances.

A criterion for static stability of systems is presented together with formulas for the calculation of the two-, three- and four-machine cases.

It is shown that the maximum angle between machines for which synchronism can be maintained is, in general, somewhat dependent upon the inertia of the synchronous machines. Under some conditions synchronism can be maintained between two machines operating at angles greater than $\pi/2$. The delivered power corresponding to definite excitation of machines will, in general, be a maximum for a smaller angle than the maximum stable angle. While the investigations have shown that synchronism can be maintained in regions heretofore considered inherently unstable, operation in such regions is held to be inadvisable.

There are a number of generalizations which may be made as to the limiting stable condition.

For the two-machine problem the limiting angle is (*a*) $\pi/2$ when the inertias are equal, and (*b*) is greater or less than $\pi/2$ when the inertia of the receiving apparatus is greater or less than the inertia of the supply apparatus, respectively, and (*c*) is equal to $\pi/2$ and independent of inertia when resistance is negligible.

The limiting stable angle with one or two intermediate condensers of zero impedance and system resistance negligible is $\pi/2$ between adjacent sources of e. m. f. With finite-impedance condensers on a symmetrical system with resistance negligible the limiting angle is independent of the inertia of any of the machines.

The results of calculations of the stability of practical transmission lines indicate that large increases in static limits are obtainable with intermediate condensers. Small variation from the theoretically best location has relatively little influence on the stability limit. The improvement in stability due to an intermediate condenser is of course larger with low values of machine impedance but even a high-impedance condenser of the synchronous type will show marked advantage over static condensers which are unsuitable for this application.

Appendix I

Development of the Criterion for Stability Four-Machine Problem

Problems involving four synchronous sources of e. m. f. such as synchronous generators, motors, and condensers have been termed "four-machine" problems. In the following, a criterion will be developed which when applied to a certain operating condition will enable one to determine whether the system is stable or unstable for that condition.

Consider the internal voltages of the four machines, constant and equal to $\mathbf{E}_a$, $\mathbf{E}_b$, $\mathbf{E}_c$, and $\mathbf{E}_d$, (to neutral) respectively. Regardless of the complexity of the system, assuming only that all loads and connecting networks may be considered as having characteristics of impedances, such as, resistors, inductors, and condensers, the current at the different machines may be expressed by the four following equations: (Impedances of machines are to be included as part of the network).

$$\left.\begin{aligned}
\mathbf{I}_a &= \mathbf{Y}_{aa}\,\mathbf{E}_a - \mathbf{Y}_{ab}\,\mathbf{E}_b - \mathbf{Y}_{ac}\,\mathbf{E}_c - \mathbf{Y}_{ad}\,\mathbf{E}_d \\
\mathbf{I}_b &= -\mathbf{Y}_{ba}\,\mathbf{E}_a + \mathbf{Y}_{bb}\,\mathbf{E}_b - \mathbf{Y}_{bc}\,\mathbf{E}_c - \mathbf{Y}_{bd}\,\mathbf{E}_d \\
\mathbf{I}_c &= -\mathbf{Y}_{ca}\,\mathbf{E}_a - \mathbf{Y}_{cb}\,\mathbf{E}_b + \mathbf{Y}_{cc}\,\mathbf{E}_c - \mathbf{Y}_{cd}\,\mathbf{E}_d \\
\mathbf{I}_d &= -\mathbf{Y}_{da}\,\mathbf{E}_a - \mathbf{Y}_{db}\,\mathbf{E}_b - \mathbf{Y}_{dc}\,\mathbf{E}_c + \mathbf{Y}_{dd}\,\mathbf{E}_d
\end{aligned}\right\} \quad (48)$$

Letting the phase voltages be, respectively

$$\left.\begin{aligned}
\mathbf{E}_{\mathrm{A}} &= E_{\mathrm{A}}\,\epsilon^{j\phi_a} \\
\mathbf{E}_{\mathrm{B}} &= E_{\mathrm{B}}\,\epsilon^{j\phi_b} \\
\mathbf{E}_{\mathrm{C}} &= E_{\mathrm{C}}\,\epsilon^{j\phi_c} \\
\mathbf{E}_{\mathrm{D}} &= E_{\mathrm{D}}\,\epsilon^{j\phi_d}
\end{aligned}\right\} \quad (49)$$

and since

$$P_a + j\,Q_a = 3\,\mathbf{E}_a\,\mathfrak{I}_a \quad (50)$$

one may write:

$$\left.\begin{aligned}
P_a + j\,Q_a &= +\,\mathfrak{Y}_{aa}\,E_{\mathrm{A}}^2 - \mathfrak{Y}_{ab}\,E_{\mathrm{A}}\,E_{\mathrm{B}}\,\epsilon^{j(\phi_a-\phi_b)} \\
&\quad - \mathfrak{Y}_{ac}\,E_{\mathrm{A}}\,E_{\mathrm{C}}\,\epsilon^{j(\phi_a-\phi_c)} - \mathfrak{Y}_{ad}\,E_{\mathrm{A}}\,E_{\mathrm{D}}\,\epsilon^{j(\phi_a-\phi_d)} \\
P_b + j\,Q_b &= -\,\mathfrak{Y}_{ba}\,E_{\mathrm{B}}\,E_{\mathrm{A}}\,\epsilon^{j(\phi_b-\phi_a)} + \mathfrak{Y}_{bb}\,E_b^2 \\
&\quad - \mathfrak{Y}_{bc}\,E_{\mathrm{B}}\,E_{\mathrm{C}}\,\epsilon^{j(\phi_b-\phi_c)} - \mathfrak{Y}_{bd}\,E_{\mathrm{B}}\,E_{\mathrm{D}}\,\epsilon^{j(\phi_b-\phi_d)} \\
P_c + j\,Q_c &= -\,\mathfrak{Y}_{ca}\,E_{\mathrm{C}}\,E_{\mathrm{A}}\,\epsilon^{j(\phi_c-\phi_a)} \\
&\quad - \mathfrak{Y}_{cb}\,E_{\mathrm{C}}\,E_{\mathrm{B}}\,\epsilon^{j(\phi_c-\phi_b)} + \mathfrak{Y}_{cc}\,E_c^{\,2} \\
&\quad - \mathfrak{Y}_{cd}\,E_{\mathrm{C}}\,E_{\mathrm{D}}\,\epsilon^{j(\phi_c-\phi_d)} \\
P_d + j\,Q_d &= -\,\mathfrak{Y}_{da}\,E_{\mathrm{D}}\,E_{\mathrm{A}}\,\epsilon^{j(\phi_d-\phi_a)} \\
&\quad - \mathfrak{Y}_{db}\,E_{\mathrm{D}}\,E_{\mathrm{B}}\,\epsilon^{j(\phi_d-\phi_b)} \\
&\quad - \mathfrak{Y}_{dc}\,E_{\mathrm{D}}\,E_{\mathrm{C}}\,\epsilon^{j(\phi_d-\phi_c)} + \mathfrak{Y}_{dd}\,E_{\mathrm{D}}^2
\end{aligned}\right\} \quad (50)$$

Now let

$$\begin{aligned}
\phi_a - \phi_b &= \phi_x \\
\phi_b - \phi_c &= \phi_y \\
\phi_c - \phi_d &= \phi_z
\end{aligned}$$

and

$$\left.\begin{aligned}
\mathbf{Y}_{ab} &= Y_{ab}\,\epsilon^{j\phi_1} \\
\mathbf{Y}_{bc} &= Y_{bc}\,\epsilon^{j\phi_2} \\
\mathbf{Y}_{ca} &= Y_{ca}\,\epsilon^{j\phi_3} \\
\mathbf{Y}_{ad} &= Y_{ad}\,\epsilon^{j\phi_4} \\
\mathbf{Y}_{bd} &= Y_{bd}\,\epsilon^{j\phi_5} \\
\mathbf{Y}_{cd} &= Y_{cd}\,\epsilon^{j\phi_6} \\
\mathbf{Y}_{aa} &= Y_{aa}\,\epsilon^{j\phi_7} \\
\mathbf{Y}_{bb} &= Y_{bb}\,\epsilon^{j\phi_8} \\
\mathbf{Y}_{cc} &= Y_{cc}\,\epsilon^{j\phi_9} \\
\mathbf{Y}_{dd} &= Y_{dd}\,\epsilon^{j\phi_{10}}
\end{aligned}\right\} \quad (52)$$

$$\left.\begin{aligned}
P_a &= Y_{aa} E_A^2 \cos \phi_7 - Y_{ab} E_A E_B \cos (\phi_x - \phi_1) \\
&\quad - Y_{ac} E_A E_C \cos (\phi_x + \phi_y - \phi_3) \\
&\quad - Y_{ad} E_A E_D \cos (\phi_x + \phi_y + \phi_z - \phi_4) \\
P_b &= - Y_{ab} E_A E_B \cos (+ \phi_x + \phi_1) + Y_{bb} E_B^2 \cos \phi_8 \\
&\quad - Y_{bc} E_B E_C \cos (\phi_y - \phi_2) \\
&\quad - Y_{bd} E_B E_D \cos (\phi_y + \phi_z - \phi_5 \\
P_c &= - Y_{ac} E_A E_C \cos (+ \phi_x + \phi_y + \phi_3) \\
&\quad - Y_{bc} E_B E_C \cos (\phi_y + \phi_2) \\
&\quad + Y_{cc} E_C^2 \cos \phi_9 - Y_{cd} E_C E_D \cos (+ \phi_z - \phi_6) \\
P_d &= - Y_{ad} E_A E_D \cos (\phi_x + \phi_y + \phi_z + \phi_4) \\
&\quad - Y_{bd} E_B E_D \cos (+ \phi_y + \phi_z + \phi_5) \\
&\quad - Y_{cd} E_C E_D \cos (\phi_z + \phi_6) + Y_{dd} E_D^2 \cos \phi_{10}
\end{aligned}\right\} \tag{53}$$

In analyzing the conditions for stable operation at a given operating point several criteria suggest themselves. One of the rotors can be displaced forcibly from its position of equilibrium and the relations analyzed to determine whether it will return to its original position. An increment of load could be placed on the shaft of one unit and the conditions investigated for stable operation. Another disturbance suggests itself in decreasing the network load by changing the network constants. The latter two involve a change in frequency or governor setting to determine the final steady state operating conditions. For this reason the change in angular position constituting the disturbing factor will be selected.

In any machine transient the difference between input and output power determines the power which must be supplied or absorbed by the rotor and consequently the deceleration or acceleration of the rotor and internal voltage. Governors are much too sluggish in action to rely upon their action to save the system from pulling out and for that reason one can consider the input constant. So that for constant governor settings P_{ga}, P_{gb}, P_{gc}, and P_{gd}, and stored mechanical energy W_a, W_b, W_c, and W_d (in kw. sec. at synchronous speed) and using the relation $\alpha = \frac{180 f}{W} \Delta P$, the corresponding accelerations may be written as follows:

$$\left.\begin{aligned}
\alpha_a &= \frac{180 f}{W_a} [P_{ga} - P_a] \\
\alpha_b &= \frac{180 f}{W_b} [P_{gb} - P_b] \\
\alpha_c &= \frac{180 f}{W_c} [P_{gc} - P_c] \\
\alpha_d &= \frac{180 f}{W_d} [P_{gd} - P_d]
\end{aligned}\right\} \tag{54}$$

In this investigation one is not interested as to whether the system as a whole will accelerate or decelerate which is determined by whether the sum of the governor settings P_{ga}, etc., is greater or less than the load, but rather in whether the system will pull apart. One is interested in the time rate of change of the difference in angles between the internal voltages, *i. e.*, in the time rate of change of ϕ_x, ϕ_y, and ϕ_z.

But

$$\left.\begin{aligned}
\frac{d^2 \phi_x}{d t^2} &= \alpha_x = \alpha_a - \alpha_b \\
\frac{d^2 \phi_y}{d t^2} &= \alpha_y = \alpha_b - \alpha_c \\
\frac{d^2 \phi_z}{d t^2} &= \alpha_z = \alpha_c - \alpha_d
\end{aligned}\right\} \tag{55}$$

Therefore,

$$\begin{aligned}
\alpha_x = {} & \frac{180 f}{W_a} P_{ga} - \frac{180 f}{W_b} P_{gb} \\
& - \frac{180 f}{W_a} Y_{aa} E_A^2 \cos \phi_7 + \frac{180 f}{W_b} Y_{bb} E_B^2 \cos \phi_8 \\
& + \frac{180 f}{W_a} [Y_{ab} E_A E_B \cos (\phi_x - \phi_1) \\
& + Y_{ac} E_A E_C \cos (\phi_x + \phi_y - \phi_3) \\
& + Y_{ad} E_A E_D \cos (\phi_x + \phi_y + \phi_z - \phi_4)] \\
& - \frac{180 f}{W_b} [Y_{ab} E_A E_B \cos (\phi_x + \phi_1) \\
& + Y_{bc} E_B E_C \cos (\phi_y - \phi_2) \\
& + Y_{bd} E_B E_D \cos (\phi_y + \phi_z - \phi_5)]
\end{aligned} \tag{56}$$

$$\begin{aligned}
\alpha_y = {} & \frac{180 f}{W_b} P_{gb} - \frac{180 f}{W_c} P_{gc} \\
& - \frac{180 f}{W_b} Y_{bb} E_B^2 \cos \phi_8 + \frac{180 f}{W_c} Y_{cc} E_C^2 \cos \phi_9 \\
& + \frac{180 f}{W_b} [Y_{ab} E_A E_B \cos (\phi_x + \phi_1) \\
& + Y_{bc} E_B E_C \cos (\phi_y - \phi_2) \\
& + Y_{bd} E_B E_D \cos (\phi_y + \phi_z - \phi_5)] \\
& - \frac{180 f}{W_c} [Y_{ac} E_A E_C \cos (\phi_x + \phi_y + \phi_3) \\
& + Y_{bc} E_B E_C \cos (\phi_y + \phi_2) + Y_{cd} E_C E_D \cos (\phi_z - \phi_6)]
\end{aligned} \tag{57}$$

$$\begin{aligned}
\alpha_z = {} & \frac{180 f}{W_c} P_{gc} - \frac{180 f}{W_d} P_{gd} \\
& - \frac{180 f}{W_c} Y_{cc} E_C^2 \cos \phi_9 + \frac{180 f}{W_d} Y_{dd} E_D^2 \cos \phi_{10} \\
& + \frac{180 f}{W_c} [Y_{ac} E_A E_C \cos (\phi_x + \phi_y + \phi_3)
\end{aligned}$$

$$+ Y_{bc} E_B E_C (\phi_y + \phi_2)$$
$$+ Y_{cd} E_C E_D \cos(\phi_z - \phi_6)]$$
$$- \frac{180 f}{W_d} [Y_{ad} E_A E_D \cos(\phi_x + \phi_y + \phi_z + \phi_4)$$
$$+ Y_{bd} E_B E_D \cos(\phi_y + \phi_z + \phi_5)$$
$$+ Y_{cd} E_C E_D \cos(\phi_z + \phi_6)] \quad (58)$$

These equations completely determine the oscillations between machines for the given circuit conditions, voltages, and governor settings. Each expression for acceleration $\frac{d^2 \phi_x}{d t^2}$ etc., is a complicated function of the angles ϕ_x, ϕ_y, and ϕ_z which are variable during the oscillations. No method is known whereby this type of oscillation can be calculated accurately by analytical methods. Step-by-step solutions are always possible. For small variations from the mean angles the following method may be used.

$$\left.\begin{aligned} \Delta \alpha_x &= \frac{\partial \alpha_x}{\partial \phi_x} \Delta \phi_x + \frac{\partial \alpha_x}{\partial \phi_y} \Delta \phi_y + \frac{\partial \alpha_x}{\partial \phi_z} \Delta \phi_z \\ \Delta \alpha_y &= \frac{\partial \alpha_y}{\partial \phi_x} \Delta \phi_x + \frac{\partial \alpha_y}{\partial \phi_y} \Delta \phi_y + \frac{\partial \alpha_y}{\partial \phi_z} \Delta \phi_z \\ \Delta \alpha_z &= \frac{\partial \alpha_z}{\partial \phi_x} \Delta \phi_x + \frac{\partial \alpha_z}{\partial \phi_y} \Delta \phi_y + \frac{\partial \alpha_z}{\partial \phi_z} \Delta \phi_z \end{aligned}\right\} \quad (59)$$

Let

$$\left.\begin{aligned} &\frac{\partial \alpha_x}{\partial \phi_x} = K_1 \quad \frac{\partial \alpha_y}{\partial \phi_x} = K_4 \quad \frac{\partial \alpha_z}{\partial \phi_x} = K_7 \\ &\frac{\partial \alpha_x}{\partial \phi_y} = K_2 \quad \frac{\partial \alpha_y}{\partial \phi_y} = K_5 \quad \frac{\partial \alpha_z}{\partial \phi_y} = K_8 \\ &\frac{\partial \alpha_x}{\partial \phi_z} = K_3 \quad \frac{\partial \alpha_y}{\partial \phi_z} = K_6 \quad \frac{\partial \alpha_z}{\partial \phi_z} = K_9 \end{aligned}\right\} \quad (60)$$

then

$$\left.\begin{aligned} \Delta \alpha_x &= K_1 \Delta \phi_x + K_2 \Delta \phi_y + K_3 \Delta \phi_z \\ \Delta \alpha_y &= K_4 \Delta \phi_x + K_5 \Delta \phi_y + K_6 \Delta \phi_z \\ \Delta \alpha_z &= K_7 \Delta \phi_x + K_8 \Delta \phi_y + K_9 \Delta \phi_z \end{aligned}\right\} \quad (61)$$

If the mean angles during the oscillations, *i. e.*, the stationary values without oscillations be ϕ_{x0}, ϕ_{y0}, and ϕ_{z0}, and the variations from these values be θ_x, θ_y, and θ_z, then

$$\left.\begin{aligned} \phi_x &= \phi_{x0} + \theta_x \\ \phi_y &= \phi_{y0} + \theta_y \\ \phi_z &= \phi_{z0} + \theta_z \end{aligned}\right\} \quad (62)$$

or

$$\left.\begin{aligned} \Delta \phi_x &= \theta_x \\ \Delta \phi_y &= \theta_y \\ \Delta \phi_z &= \theta_z \end{aligned}\right\} \quad (63)$$

In addition

$$\left.\begin{aligned} \alpha_x &= \frac{d^2 \phi_x}{d t^2} = \frac{d^2 \theta_x}{d t^2} \\ \alpha_y & \;\; \frac{d^2 \phi_y}{d t^2} = \frac{d^2 \theta_y}{d t^2} \\ \alpha_z &= \frac{d^2 \phi_z}{d t^2} = \frac{d^2 \theta_z}{d t^2} \end{aligned}\right\} \quad (64)$$

Since α_x, α_y and α_z, are equal to zero for steady conditions, *i. e.*, for

$$\phi_x = \phi_{x0}$$
$$\phi_y = \phi_{y0}$$
$$\phi_z = \phi_{z0}$$

one may write

$$\left.\begin{aligned} \Delta \alpha_x &= \alpha_x \\ \Delta \alpha_y &= \alpha_y \\ \Delta \alpha_z &= \alpha_z \end{aligned}\right\} \quad (65)$$

so that, substituting in the previous equations, (61), containing K_1, K_2, K_3, etc.

$$\left.\begin{aligned} \frac{d^2 \theta_x}{d t^2} &= K_1 \theta_x + K_2 \theta_y + K_3 \theta_z \\ \frac{d^2 \theta_y}{d t^2} &= K_4 \theta_x + K_5 \theta_y + K_6 \theta_z \\ \frac{d^2 \theta_z}{d t^2} &= K_7 \theta_x + K_8 \theta_y + K_9 \theta_z \end{aligned}\right\} \quad (66)$$

These simultaneous differential equations may be solved by, letting

$$\left.\begin{aligned} \theta_x &= A\, \epsilon^{mt} \\ \theta_y &= B\, \epsilon^{mt} \\ \theta_z &= C\, \epsilon^{mt} \end{aligned}\right\} \quad (67)$$

By substituting in equation (66)

$$\left.\begin{aligned} m^2 A &= K_1 A + K_2 B + K_3 C \\ m^2 B &= K_4 A + K_5 B + K_6 C \\ m^2 C &= K_7 A + K_8 B + K_9 C \end{aligned}\right\} \quad (68)$$

Rearranging

$$K_2 \frac{B}{A} + K_3 \frac{C}{A} + (K_1 - m^2) = 0$$

$$(K_5 - m^2) \frac{B}{A} + K_6 \frac{C}{A} = - K_4$$

$$K_8 \frac{B}{A} + (K_9 - m^2) \frac{C}{A} = - K_7$$

From the last two equations

$$\frac{B}{A} = \frac{\begin{vmatrix} -K_4, & K_6 \\ -K_7, & (K_9 - m^2) \end{vmatrix}}{\begin{vmatrix} (K_5 - m^2), & K_6 \\ K_8, & (K_9 - m^2) \end{vmatrix}}$$

$$\frac{C}{A} = \frac{\begin{vmatrix} (K_5 - m^2), & -K_4 \\ K_8, & -K_7 \end{vmatrix}}{\begin{vmatrix} (K_5 - m^2), & K_6 \\ K_8, & (K_9 - m^2) \end{vmatrix}}$$

Substituting these values of $\frac{B}{A}$ and $\frac{C}{A}$ in the first equation

$$K_2 \begin{vmatrix} -K_4, & K_6 \\ -K_7, & (K_9 - m^2) \end{vmatrix} + K_3 \begin{vmatrix} (K_5 - m^2), & -K_4 \\ K_8, & -K_7 \end{vmatrix} + (K_1 - m^2) \begin{vmatrix} (K_5 - m^2), & K_6 \\ K_8, & (K_9 - m^2) \end{vmatrix} = 0 \qquad (69)$$

Expanded this becomes a bi-cubic equation

$$m^6 + a\,m^4 + b\,m^2 + c = 0 \qquad (70)$$

in which

$$\left.\begin{aligned} a &= -(K_1 + K_5 + K_9) \\ b &= K_1 K_5 + K_1 K_9 + K_5 K_9 - K_2 K_4 - K_3 K_7 - K_6 K_8 \\ c &= K_1 K_6 K_8 + K_2 K_4 K_9 + K_3 K_5 K_7 - K_1 K_5 K_9 \\ &\quad - K_2 K_6 K_7 - K_3 K_4 K_8 \end{aligned}\right\} \qquad (71)$$

The condition that the system be stable for small disturbances such as the displacement of one or more rotors from its normal position is that all the roots of the cubic in m^2 be negative. In this case the six roots of the bi-cubic equation will be purely imaginary. Any disturbance results in an oscillation of constant amplitude. The formulas do not take damping into consideration, but from the physical consideration of the problem it is known that the oscillation will be damped out by copper losses, etc. If any of the roots of the cubic in m^2 are other than negative real numbers, either positive real or complex, one or more of the roots in m will be of the form $(r + j\,s)$, $(r - j\,s)$, or $(r + j\,0)$ in which r is positive. This results in a term for θ_x, θ_y, and θ_z of the form $A\,\epsilon^{(r+js)t}$, $A\,\epsilon^{(r-js)t}$, or $A\,\epsilon^{rt}$. In any case the term increases indefinitely as a function of time.

The condition that all the roots of the cubic in M^2 be real and negative, requires that certain relations exist between the coefficients a, b, and c. This relation may be investigated by the application of Stürms theorem, from which the following conditions are obtained for the disturbance to be oscillatory, *i.e.*, for the system to be stable.

$$\left.\begin{aligned} & c > 0 \\ & b > 0 \\ & a\,b - 9\,c > 0 \\ & \Delta - b > 0 \ldots (a\,b - 9\,c)(4\,a^3 - 15\,a\,b + 27\,c) \\ & \qquad - 4\,b\,(a^2 - 3\,b)^2 > 0 \\ & a^2 - 3\,b < 0 \end{aligned}\right\} \qquad (72)$$

The coefficients a, b, and c, are functions of K_1, K_2, K_3, etc., and the latter, functions of the angles ϕ_x, ϕ_y, and ϕ_z. The K coefficients will next be evaluated. Since $(180\,f)$ occurs as a coefficient of each K, it may be neglected. In what follows, therefore, the term $(180\,f)$ will be omitted.

$$K_1 = \frac{\partial\,\alpha_x}{\partial\,\phi_x} = -\frac{Y_{ab}\,E_A\,E_B}{W_a}\sin(\phi_x - \phi_1) - \frac{Y_{ac}\,E_A\,E_C}{W_a}\sin(\phi_x + \phi_y - \phi_3) - \frac{Y_{ad}\,E_A\,E_D}{W_a}\sin(\phi_x + \phi_y + \phi_z - \phi_4) + \frac{Y_{ab}\,E_A\,E_B}{W_b}\sin(\phi_x + \phi_1)$$

$$K_2 = \frac{\partial\,\alpha_x}{\partial\,\phi_y} = -\frac{Y_{ac}\,E_A\,E_C}{W_a}\sin(\phi_x + \phi_y - \phi_3) - \frac{Y_{ad}\,E_A\,E_D}{W_a}\sin(\phi_x + \phi_y + \phi_z - \phi_4) + \frac{Y_{bc}\,E_B\,E_C}{W_b}\sin(\phi_y - \phi_2) + \frac{Y_{bd}\,E_B\,E_D}{W_b}\sin(\phi_y + \phi_z - \phi_5)$$

$$K_3 = \frac{\partial\,\alpha_x}{\partial\,\phi_z} = -\frac{Y_{ad}\,E_A\,E_D}{W_a}\sin(\phi_x + \phi_y + \phi_z - \phi_4) + \frac{Y_{bd}\,E_B\,E_D}{W_b}\sin(\phi_y + \phi_z - \phi_5)$$

$$K_4 = \frac{\partial\,\alpha_y}{\partial\,\phi_x} = -\frac{Y_{ab}\,E_A\,E_B}{W_b}\sin(\phi_x + \phi_1) + \frac{Y_{ac}\,E_A\,E_C}{W_c}\sin(\phi_x + \phi_y + \phi_3)$$

$$K_5 = \frac{\partial\,\alpha_y}{\partial\,\phi_y} = -\frac{Y_{bc}\,E_B\,E_C}{W_b}\sin(\phi_y - \phi_2) - \frac{Y_{bd}\,E_B\,E_D}{W_b}\sin(\phi_y + \phi_z - \phi_5) + \frac{Y_{ac}\,E_A\,E_C}{W_c}\sin(\phi_x + \phi_y + \phi_3) + \frac{Y_{bc}\,E_B\,E_C}{W_c}\sin(\phi_y + \phi_2)$$

$$K_6 = \frac{\partial\,\alpha_y}{\partial\,\phi_z} = -\frac{Y_{bd}\,E_B\,E_D}{W_b}\sin(\phi_y + \phi_z - \phi_5) + \frac{Y_{cd}\,E_C\,E_D}{W_c}\sin(\phi_z - \phi_6)$$

$$K_7 = \frac{\partial\,\alpha_z}{\partial\,\phi_x} = -\frac{Y_{ac}\,E_A\,E_C}{W_c}\sin(\phi_x + \phi_y + \phi_3) + \frac{Y_{ad}\,E_A\,E_D}{W_d}\sin(\phi_x + \phi_y + \phi_z + \phi_4)$$

$$K_8 = \frac{\partial\,\alpha_z}{\partial\,\phi_y} = -\frac{Y_{ac}\,E_A\,E_C}{W_c}\sin(\phi_x + \phi_y + \phi_3) - \frac{Y_{bc}\,E_B\,E_C}{W_c}\sin(\phi_y + \phi_2) + \frac{Y_{ad}\,E_A\,E_D}{W_d}\sin(\phi_x + \phi_y + \phi_z + \phi_4) + \frac{Y_{bd}\,E_B\,E_D}{W_d}\sin(\phi_y + \phi_z + \phi_5)$$

$$K_9 = \frac{\partial\,\alpha_z}{\partial\,\phi_z} = -\frac{Y_{cd}\,E_C\,E_D}{W_c}\sin(\phi_z - \phi_6) + \frac{Y_{ad}\,E_A\,E_D}{W_d}\sin(\phi_x + \phi_y + \phi_z + \phi_4) + \frac{Y_{bd}\,E_B\,E_D}{W_d}\sin(\phi_y + \phi_z + \phi_5) + \frac{Y_{cd}\,E_C\,E_D}{W_d}\sin(\phi_z + \phi_6)$$

Or letting

$$\left.\begin{aligned}
A &= +\frac{Y_{ab}\,E_A\,E_B}{W_b}\sin(\phi_x + \phi_1)\\
B &= +\frac{Y_{ab}\,E_A\,E_B}{W_a}\sin(\phi_x - \phi_1)\\
C &= +\frac{Y_{bc}\,E_B\,E_C}{W_c}\sin(\phi_y + \phi_2)\\
D &= +\frac{Y_{bc}\,E_B\,E_C}{W_b}\sin(\phi_y - \phi_2)\\
E &= +\frac{Y_{ac}\,E_A\,E_C}{W_c}\sin(\phi_x + \phi_y + \phi_3)
\end{aligned}\right\} \quad (73)$$

$$\left.\begin{aligned}
F &= +\frac{Y_{ac}\,E_A\,E_C}{W_a}\sin(\phi_x + \phi_y - \phi_3)\\
G &= +\frac{Y_{cd}\,E_C\,E_D}{W_d}\sin(\phi_z + \phi_6)\\
H &= +\frac{Y_{cd}\,E_C\,E_D}{W_c}\sin(\phi_z - \phi_6)\\
I &= +\frac{Y_{bd}\,E_B\,E_D}{W_d}\sin(\phi_y + \phi_z + \phi_5)\\
J &= +\frac{Y_{bd}\,E_B\,E_D}{W_b}\sin(\phi_y + \phi_z - \phi_5)\\
K &= +\frac{Y_{ad}\,E_A\,E_D}{W_d}\sin(\phi_x+\phi_y+\phi_z+\phi_4)\\
L &= +\frac{Y_{ad}\,E_A\,E_D}{W_a}\sin(\phi_x+\phi_y+\phi_z-\phi_4)
\end{aligned}\right\} \quad \text{(73) Continued}$$

$$\left.\begin{aligned}
K_1 &= A - B - F - L\\
K_2 &= D - F + J - L\\
K_3 &= J - L\\
K_4 &= -A + E\\
K_5 &= C - D + E - J\\
K_6 &= H - J\\
K_7 &= -E + K\\
K_8 &= -C - E + I + K\\
K_9 &= G - H + I + K
\end{aligned}\right\} \quad (74)$$

Three-Machine Problem

The criterion for stability for a three-machine problem may be obtained almost directly from the results of the four-machine problem. The circuit conditions for this case are defined completely by the following equations.

$$\begin{aligned}
\mathbf{I}_a &= \mathbf{Y}_{aa}\,\mathbf{E}_a - \mathbf{Y}_{ab}\,\mathbf{E}_b - \mathbf{Y}_{ac}\,\mathbf{E}_c\\
\mathbf{I}_b &= -\mathbf{Y}_{ba}\,\mathbf{E}_a + \mathbf{Y}_{bb}\,\mathbf{E}_b - \mathbf{Y}_{bc}\,\mathbf{E}_c\\
\mathbf{I}_c &= -\mathbf{Y}_{ca}\,\mathbf{E}_a - \mathbf{Y}_{cb}\,\mathbf{E}_b + \mathbf{Y}_{cc}\,\mathbf{E}_c
\end{aligned}$$

Comparing these equations with those for the four-machine problem they will be seen to be identical if $\mathbf{Y}_{ad} = \mathbf{Y}_{bd} = \mathbf{Y}_{cd} = \mathbf{Y}_{dd} = 0$.

The corresponding values for the K constants become

$$\left.\begin{aligned}
K_1 &= A - B - F\\
K_2 &= D - F\\
K_3 &= 0\\
K_4 &= -A + E\\
K_5 &= C - D + E\\
K_6 &= 0\\
K_7 &= -E\\
K_8 &= -C - E\\
K_9 &= 0
\end{aligned}\right\} \quad (75)$$

On substitution of these values for the K constants in equations (**71**), they reduce to

$$\left.\begin{aligned} a &= -(K_1 + K_5) \\ b &= K_1 K_5 - K_2 K_4 \\ c &= 0 \end{aligned}\right\} \qquad (\mathbf{76})$$

and since $c = 0$, equation (**70**) reduces to

$$M^4 + a M^2 + b = 0 \qquad (\mathbf{77})$$

The condition that the roots of this quadratic in M^2 be negative are that

$$\left.\begin{aligned} b &> 0 \\ a &> 0 \\ a^2 &> 4\,b \end{aligned}\right\} \qquad (\mathbf{78})$$

Two-Machine Problem

The results obtained previously for the two-machine problem in the body of the paper could have been obtained more simply but with probably less clearness by letting all the admittance coefficients but $\mathbf{Y}_{aa}$, $\mathbf{Y}_{bb}$, and $\mathbf{Y}_{ab}$ in equations (**48**) for the four-machine problem equal zero. After determining the K constants and substituting them in the a, b, and c constants, the resultant equation becomes

$$x^2 + a = 0 \qquad (\mathbf{79})$$

in which

$$a = -K_1 \qquad (\mathbf{80})$$

$$= -Y_{ab} E_A E_B \left[\frac{1}{W_b} \sin(\phi_{x0} + \phi_1) - \frac{1}{W_a} \sin(\phi_{x0} - \phi_1) \right]$$

or the condition that operation be stable is that

$$\frac{1}{W_b} \sin(\phi_{x0} + \phi_1) - \frac{1}{W_a} \sin(\phi_{x0} - \phi_1) < 0$$

or that

$$\phi_{x0} < \tan^{-1} \frac{W_a + W_b}{W_b - W_a} \tan \phi_1 \qquad (\mathbf{81})$$

which checks results obtained by the more detailed method.

Appendix II

Static Stability Limits with Loads that do not Vary as Ordinary Impedances

Induction motors and synchronous motors, driving pumps, fans, etc., possess a load characteristic which is essentially one of constant shaft torque, or constant power; and lamp loads and converters vary as the square of the voltage. These loads can always be combined so that the composite result shows the variation of real power P and reactive power Q with voltage. The $\frac{dP}{dE}$ and $\frac{dQ}{DE}$ for the load may, therefore, be considered known. With fixed internal voltages (magnitude only) at a and b in Fig. 27 and the load at C, what is the criterion for system stability?

The currents at the three points a, b, and c are connected by the following relations

$$\mathbf{I}_a = \mathbf{Y}_{aa}\mathbf{E}_a - \mathbf{Y}_{ab}\mathbf{E}_b - \mathbf{Y}_{ac}\mathbf{E}_c$$
$$\mathbf{I}_b = -\mathbf{Y}_{ab}\mathbf{E}_a + \mathbf{Y}_{bb}\mathbf{E}_b - \mathbf{Y}_{bc}\mathbf{E}_c$$
$$\mathbf{I}_c = -\mathbf{Y}_{ca}\mathbf{E}_a - \mathbf{Y}_{bc}\mathbf{E}_b + \mathbf{Y}_{cc}\mathbf{E}_c$$

Using the same notation as in the four-machine problem,

$$P_c = -Y_{ac} E_A E_C \cos(\phi_x + \phi_y + \phi_3) - Y_{bc} E_B E_C \cos(\phi_y + \phi_2) + Y_{cc} E_c^2 \cos \phi_9 \qquad (\mathbf{92})$$

$$Q_c = +Y_{ca} E_A E_C \sin(\phi_x + \phi_y + \phi_3) + Y_{bc} E_B E_C \sin(\phi_y + \phi_2) - Y_{cc} E_c^2 \sin \phi_9 \qquad (\mathbf{93})$$

Let

$$\phi_x = \phi_{x0} + \theta_x$$
$$\phi_y = \phi y_0 + \theta_y$$
$$E_c = E_{c0} + e_c$$
$$P = P_0 + p$$
$$Q = Q_0 + q$$

In which the terms with the zero subscript represents

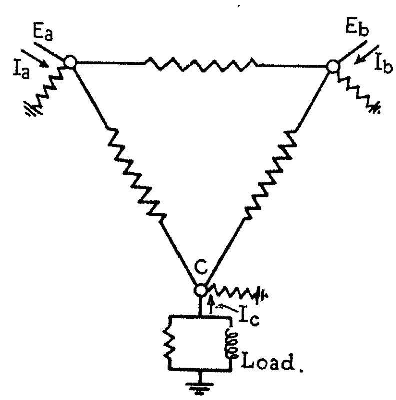

Fig. 27

the mean values and the other term the variations for small oscillations.

For small values of θ_x, θ_y, and e_c

$$\Delta P = p = \frac{\partial P_c}{\partial \phi_x}\theta_x + \frac{\partial P_c}{\partial \phi_y}\theta_y + \frac{\partial P_c}{\partial E_c} e_c \qquad (\mathbf{94})$$

$$\begin{aligned} &= +Y_{ac} E_A E_C \sin(\phi_{x0} + \phi_{y0} + \phi_3)\,.\,\theta_x \\ &\quad + [+Y_{ac} E_a E_c \sin(\phi_{x0} + \phi_{y0} + \phi_3) + Y_{bc} E_B E_C \sin(\phi_{y0} + \phi_2)]\,.\,\theta_y \\ &\quad + [-Y_{ac} E_A \cos(\phi_{x0} + \phi_{y0} + \phi_3) - Y_{bc} E_B \cos(\phi_{y0} + \phi_2) + 2\,Y_{cc} E_C \cos \phi_9]\, e_c \end{aligned} \qquad (\mathbf{95})$$

or

$$= C_1 \theta_x + C_2 \theta_y + C_3 e_c \qquad (\mathbf{96})$$

Similarly

$$\Delta Q = q = \frac{\partial Q_c}{\partial \phi_x}\,\theta_x + \frac{\partial Q_c}{\partial \phi_y}\,\theta_y + \frac{\partial Q_c}{\partial E_c}\,e_c \quad (97)$$

$$= + Y_{ca} E_A E_C \cos(\phi_{x0} + \phi_{y0} + \phi_3)\,.\,\theta_x$$
$$+ [Y_{ca} E_A E_C \cos(\phi_{x0} + \phi_{y0} + \phi_3)$$
$$+ Y_{bc} E_B E_C \cos(\phi_{y0} + \phi_2)\,]\,.\,\theta_y$$
$$+ [Y_{ca} E_A \sin(\phi_{x0} + \phi_{y0} + \phi_3)$$
$$+ Y_{bc} E_B \sin(\phi_{y0} + \phi_2) - 2\,Y_{cc} E_C \sin\phi_9]\,e_c \quad (98)$$

or

$$= C_4\,\theta_x + C_5\,\theta_y + C_6\,e_c \quad (99)$$

But p and q are also equal to:

$$p = \frac{d\,P_c}{d\,E_c}\,.\,e_c \quad (100)$$

$$q = \frac{d\,Q_c}{d\,E_c}\,.\,e_c \quad (101)$$

So that

$$\frac{d\,P_c}{d\,E_c}\,.\,e_c = C_1\,\theta_x + C_2\,\theta_y + C_3\,e_c \quad (102)$$

$$\frac{d\,Q_c}{d\,E_c}\,.\,e_c = C_4\,\theta_x + C_5\,\theta_y + C_6\,e_c \quad (103)$$

or

$$C_1\,\theta_x + C_2\,\theta_y + C_7\,e_c = 0 \quad (104)$$

$$C_4\,\theta_x + C_5\,\theta_y + C_8\,e_c = 0 \quad (105)$$

Solving these equations for θ_y and e_c

$$\theta_y = + \frac{C_4\,C_7 - C_1\,C_8}{C_2\,C_8 - C_5\,C_7}\,\theta_x \quad (106)$$

$$e_c = \frac{C_1\,C_5 - C_2\,C_4}{C_2\,C_8 - C_5\,C_7}\,\theta_x \quad (107)$$

Equation (**56**) under the discussion of the four-machine problem gives the relation for α_x applicable to this problem. For small variations in θ_x, θ_y, and e_c

$$\alpha_x = \frac{\partial\,\alpha_x}{\partial\,\phi_x}\,\theta_x + \frac{\partial\,\alpha_x}{\partial\,\phi_y}\,\theta_y + \frac{\partial\,\alpha_x}{\partial\,E_C}\,e_c \quad (108)$$

$$= C_9\,\theta_x + C_{10}\,\theta_y + C_{11}\,e_c \quad (109)$$

Substituting the above values of θ_y and e_c from equations (**106**) and (**107**) in equation (**109**)

$$\alpha_x = \left[\,C_9 + C_{10}\,\frac{C_4\,C_7 - C_1\,C_8}{C_2\,C_8 - C_5\,C_7} + C_{11}\,\frac{C_1\,C_5 - C_2\,C_4}{C_2\,C_8 - C_5\,C_7}\right]\theta_x$$

$$\alpha_x = \frac{C_9\,(C_2\,C_8 - C_5\,C_7) + C_{10}\,(C_4\,C_7 - C_1\,C_8) + C_{11}\,(C_1\,C_5 - C_2\,C_4)}{C_2\,C_8 - C_5\,C_7}\,\theta_x \quad (110)$$

As long as the coefficient of θ_x is negative the system is stable. The limit will occur when it is equal to zero. Since the denominator can never equal infinity the limit occurs when

$$C_9\,(C_2\,C_8 - C_5\,C_7) + C_{10}\,(C_4\,C_7 - C_1\,C_8) + C_{11}\,(C_1\,C_5 - C_2\,C_4) \doteq 0 \quad (111)$$

Resumé of coefficients:

$$C_1 = Y_{ac} E_A E_C \sin(\phi_{x0} + \phi_{y0} + \phi_3)$$

$$C_2 = Y_{ac} E_A E_C \sin(\phi_{x0} + \phi_{y0} + \phi_3) + Y_{bc} E_B E_C \sin(\phi_{y0} + \phi_2)$$

$$C_4 = Y_{ac} E_A E_C \cos(\phi_{x0} + \phi_{y0} + \phi_3)$$

$$C_5 = Y_{ac} E_A E_C \cos(\phi_{x0} + \phi_{y0} + \phi_3) + Y_{bc} E_B E_C \cos(\phi_{y0} + \phi_2)$$

$$C_7 = C_3 - \frac{d\,P_c}{d\,E_c}$$
$$= - Y_{ac} E_A \cos(\phi_{x0} + \phi_{y0} + \phi_3) - Y_{bc} E_B \cos(\phi_{y0} + \phi_2) + 2\,Y_{cc} E_C \cos\phi_9 - \frac{d\,P_c}{d\,E_c}$$
$$= \frac{P_c}{E_c} + Y_{cc} E_C \cos\phi_9 - \frac{d\,P_c}{d\,E_c}$$

$$C_8 = C_6 - \frac{d\,Q_c}{d\,E_c}$$
$$= Y_{ca} E_A \sin(\phi_{x0} + \phi_{y0} + \phi_3) + Y_{bc} E_B \sin(\phi_{y0} + \phi_2) - 2\,Y_{cc} E_C \sin\phi_9 - \frac{d\,Q_c}{d\,E_c}$$
$$= \frac{Q_c}{E_c} - Y_{cc} E_C \sin\phi_9 - \frac{d\,Q_c}{d\,E_c}$$

$$C_9 = - \frac{Y_{ab}}{W_a} E_A E_B \sin(\phi_{x0} - \phi_1) - \frac{Y_{ac}}{W_a} E_A E_C \sin(\phi_{x0} + \phi_{y0} - \phi_3) + \frac{Y_{ab}}{W_b} E_A E_B \sin(\phi_{x0} + \phi_1)$$

$$C_{10} = - \frac{Y_{ac}}{W_a} E_A E_C \sin(\phi_{x0} + \phi_{y0} - \phi_3) + \frac{Y_{bc}}{W_b} E_B E_C \sin(\phi_{y0} - \phi_2)$$

$$C_{11} = \frac{Y_{ac}}{W_a} E_A \cos(\phi_{x0} + \phi_{y0} - \phi_3) - \frac{Y_{bc}}{W_b} E_B \cos(\phi_y - \phi_2)$$

Stability limits were calculated for systems whose load characteristics are represented by the full lines in Fig. 7. These results were compared with similar

calculations assuming the load characteristics were those of a constant shunt admittance as represented by the dotted line on the same figure. The first case investigated consisted of a simplified system form of the system in which the impedance connecting a and b is infinite, that connecting b and c $(0 + j\ 100)$ ohms and that connecting a and c $(0 + j\ 200)$ ohms. Voltage was assumed to be maintained at 220 kv. at a and at c. Calculations were made for a large range of loads both positive and negative at b and the results showed an extremely close agreement for stability limits for the two types of load characteristics, varying not more than 5 per cent for the extreme case. In addition similar calculations were made for a practical case in which line resistance and charging current were taken into consideration. The results indicated the same close agreement, from which it may be concluded that for all static stability calculations loads not containing large synchronous machines may be represented by shunt admittances of equivalent kv-a.

Appendix III

Derivation of Acceleration Equation

$$\alpha = \frac{180\, f}{E}\, \Delta P$$

Let

α = Acceleration
T = Torque
I = Moment of Inertia
E = Stored energy
P = Instantaneous power
ω = Angular velocity
f = Frequency

In c. g. s. units

$$\alpha = \frac{T}{I}$$

$$\frac{T\, \omega^2}{2\left(\frac{1}{2}\, \omega^2\, I\right)}$$

Since

$$\frac{1}{2}\, \omega^2\, I = \text{Stored energy at any instant and}$$

$$T\, \omega = \text{Instantaneous power} = P$$

$$\alpha = \frac{\omega\, P}{2\, E} \text{ in mechanical rad. per sec. per sec.}$$

To this point α and ω have been expressed in mechanical radians. These may be converted to electrical radians by dividing both sides of the equation by the number of poles. But since these will cancel out the above expression is also true for α and ω expressed in electrical radians. Since

$$\omega = \text{Angular vel. in electrical rad. per sec.}$$
$$= 2\, \pi\, f$$
$$= \frac{2\, \pi\, f\, 360}{2\, \pi}$$
$$= 360\, f \text{ degrees per sec.}$$

Therefore

$$\alpha = \frac{180\, f}{E}\, P \text{ electrical degrees per sec. per sec.}$$

This expression is rigorously true using instantaneous values during a disturbance. A good approximation is to assume f and E constant and letting α vary only with P. For a 60 cycle system having a natural period of one second in which the total swing is 60 degrees the maximum error using this approximation is about 1 per cent.

For static stabilty calculations, however, since the departure from synchronism is inappreciable, the error introduced by this assumption is also inappreciable.

In the above formula if E is expressed in watt-sec., P should be expressed in watts and if E is expressed in kilowatt-sec., P should be expressed in kilowatts.

Conversion formula for E

$$E_{\text{in kw. sec.}} = 2.3\, (W\, R^2)\, (\text{R. P. M.})^2 \times 10^{-7}$$

$(W\, R^2)$ expressed in lb. ft.^{2}

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Discussion

F. E. Terman: An illustration that indicates the thoroughness of the authors of this paper is their discovery of the fallacy of the classical belief that the maximum angle of stable operation of a network is the angle of maximum power of transmission. In reality the angle is a little greater, permitting stable operation slightly beyond the point of maximum power. The difference between the old and the correct belief is not great, but its discovery was a real achievement.

One of the most uncertain factors in stability computations is the characteristic of the load under change of voltage. Some investigators have assumed a load that drew constant power and reactive power as the load voltage changed (approximated by a motor load), while others have assumed that the load was such as to maintain the load voltage constant at all times (equivalent to assuming a receiving synchronous condenser of infinite capacity.) The former assumption gives computed results worse than are actually to be expected, and the latter leads to an optimistic result, considerably better than can be realized in practise. The actual load is one that allows the voltage to drop during disturbances, and as the voltage drops, the power demands of the load become less, and the power factor of the load improves. The power does not drop as fast as it would with a load consisting of an admittance of constant value, so that the admittance-load characteristic used by the authors is a correct assumption only in so far as the improvement of the power factor of the actual load can be considered as off-setting the less favorable power characteristic of the real load. When the voltage fluctuation is small it is likely that a constant-admittance load would give about the same result as a practical load, but for large fluctuations, as 25 per cent, this almost certainly would not be the case.

Actually, we don't know much regarding the reactive and real power drawn by the load when the voltage is suddenly changed. I should like to see some of the power people make tests, such as dropping the voltage at a distributing center first by 5 per cent, then 10 per cent, and so on, noting the change of power and power factor caused by each drop. Such information would be invaluable for stability studies, and could be obtained without creating an appreciable disturbance to service. At present we can get correct results for the conditions assumed, but we have very little idea how correct our assumptions are.

In applying the results of the paper to present transmission practise several points must be kept in mind. The results presented in Fig. 21, giving the effect of a midpoint condenser on the power limits neglect charging current, which is an important factor on lines over 200 mi. in length. In interpreting this figure, one must also remember that it is only the lower curves that apply to ordinary conditions. This is because the ratio of voltage at the midpoint of the line to the internal voltage of the generator (not terminal voltage) is normally less than unity. Boosting the midpoint voltage abnormally high by the use of a condenser is in effect increasing the average transmission voltage and this will obviously raise the power limit. The intermediate condenser when used to make the midpoint voltage higher than the terminal voltages will give the large increase in power limit shown by Fig. 21 in the upper curves, but this is gained at the expense of a poor voltage distribution along the line, and in a large measure could be obtained by the alternative method of omitting the condenser and raising the terminal voltages a little, thus keeping a flat voltage distribution. Such a flat distribution would not put as high a voltage on the midpoint of the line as would be present when the synchronous condensers were used.

Figs. 22 and 23 have been computed for an actual transmission line that has charging current, and indicate that a large intermediate condenser is required to raise the stability limit very much. An ordinary condenser has around 100 per cent synchronous reactance (*i. e.*, sustained short-circuit current equals full-load current). On the basis of this, the curve marked 100 per cent reactance represents an installed capacity of 100,000 kv-a. and the 25 per cent reactance curve represents 400,000-kv-a. installed capacity. An inspection of Figs. 22 and 23 indicates that an intermediate condenser in the order of hundreds of thousands of kv-a. is required to give large increases in the power that can be transmitted over the line.

Even with the use of large condensers, the gains that could be expected on an actual transmission system would be much less than indicated in Figs. 22 and 23 because these figures are based on the assumption of infinite-capacity bus at the receiver. An infinite bus is one which will keep its voltage absolutely constant during all kinds of system troubles, and no actual bus comes anywhere near being an infinite bus. Dr. Bush and Mr. Booth[1] made some computations which showed that condenser equipment giving about 40 per cent increase in limit under the assumption of infinite bus at the receiver, would give less than half of this gain in power limit with a finite bus approaching ordinary characteristics. There is a large difference between the actual finite bus and the theoretical infinite bus of the curves.

To sum up the situation, it is evident that this paper indicates that the increase of power limit that can be obtained by the use of intermediate synchronous condensers of usual characteristics is small unless the intermediate condenser has a capacity of at least 100,000 kv-a. and preferably two to four times this amount. Using standard condensers of 400,000 kv-a. capacity the increase in power limits with a finite receiver bus would probably be less than 40 per cent.

This is a discouragingly small gain for the price it costs. It seems that in all probability the next step lies in the development of low-impedance condensers used in conjunction with quick-excitation systems. A 100,000-kv-a. condenser having 10 per cent leakage reactance with an instantaneously acting exciting system would give the same increase of limits as a 1,000,000-kv-a. condenser of present standard type with the usual excitation speed. Such a condenser at the midpoint, with another at the receiving bus, would do wonders toward increasing the power limit of a transmission system. A condenser of this type at the receiver would give the practical equivalent of an infinite bus, and one at the midpoint would be substantially equivalent to a condenser of zero reactance. Fig. 23 shows that the gains would be very substantial.

R. D. Evans: With reference to Dr. Terman's discussion regarding the maximum angle for which systems are stable we did not wish to emphasize the point unduly because for commercial systems the increase is not very marked. However, when several synchronous machines are being considered it is very important to have the right type of limit. In this connection it may be observed that the maximum delivered power will in general occur for an angle less than the maximum stable angle; so that for practical calculations of power systems, the methods commonly in use are, according to our views, correct.

With respect to the discussion on the characteristics of the loads, we feel considerably more optimistic than Dr. Terman. We have made tests on our shop system in order to determine the variation of real power and reactive power for changes in the

1. TRANSACTIONS A. I. E. E., 1924, p. 72.

supply voltage and have found that the methods described in the paper apply. Also we have taken a number of power-company systems and segregated the load into relatively small units and studied their characteristics. We have found their variation of real power and reactive power with respect to voltage and combined them, and obtained the results described in Figs. 6 and 7. Finally, we have taken a static load, one of constant impedance, and analyzed it from a theoretical standpoint, considering the variation in real power and reactive power, with angle and voltage as worked out in Appendix II of the paper. For these conditions also the check was very good. Of course all who are interested in the theoretical calculations would welcome any kind of test which would give the fundamental experimental data on this subject.

With respect to the curves showing the increase in power, I wish to emphasize the point, that the curves have been plotted on a conservative basis. For example, the condensers were not located at the theoretically most advantageous point, but were placed at the middle of the line regardless of the effect of the terminal equipment. The curves for 220 kv. and 110 kv., plotted in Figs. 15 and 18, are based on constant voltage on the high-voltage side, and no attempt was made to take advantage of any over-voltage.

There is another phase of this problem with respect to the static limits, which is important. The method and calculations as presented apply directly only to the limits that obtain with fixed excitation of the machines. It has been demonstrated that quick-response excitation systems under the control of suitable regulators will increase the loads which can be carried. This was first pointed out by E. B. Shand and first experimentally verified during 1925 by the authors of the present paper. We wish to make it clear that we have not included in the figures given in this paper any advantage which will accrue as a result of quick-response excitation systems.

P. L. Alger: There are two points in this paper that I wish to discuss. In the first place, the authors have concluded that under certain conditions, stability of a transmission line can be maintained beyond the impedance angle, and the exact limiting angle up to which stability can be maintained, depends upon the relative inertias of the sending and receiving-end machines.

This conclusion seems to be unreasonable, as the static stability limit is reached when the machines pull out of step so slowly that inertia effects should be negligible. What the authors have shown is that when the angle of maximum power is reached, and passed, the motor begins to slow down, the line current increases, and the generator also slows down until such time as the governor of the generator prime mover operates. If the generator inertia is sufficiently small, it will obviously retard faster than the motor, and the two ends of the line will stay in step at first. On the ninth page, the authors say—"The system as a whole will retard, reducing the frequency, but this will be taken care of by the automatic governors."

The fallacy in saying that the machines are stable beyond the angle of maximum power, lies in the assumption that the governor is able to reaccelerate the motor after it once has begun to slow down. What actually happens is that the motor and generator retard together until they have acquired an appreciably lower velocity than normal, and then the governor feeds more power to the prime mover, and the system breaks apart. The additional power reaccelerates the generator, and supplies additional power to the line, but this extra power is dissipated in extra copper losses, and the actual power received by the motor decreases. As the motor will not reaccelerate until it receives more than the power it had when it went out of step, and as it is impossible for the line to deliver more than the amount of power it did when the motor began to slow down, the motor can never be restored to speed, and so the system is unstable.

Thus, the authors have shown that when a system becomes unstable, the sending and receiving ends may stay in step while retarding up to the time the governor operates, instead of falling out of step immediately, as might have been thought. This conclusion is interesting, but is of no practical importance.

The second point that I should like to bring out is the matter of the additional condenser capacity required in order to secure a given additional amount of power over a transmission line. This ratio of additional kv-a. of installed condenser capacity to additional kw. output obtainable is the fundamental factor that determines whether the scheme of an intermediate condenser station is or is not of practical economic importance.

Fig. 21 of the paper presents curves showing the additional percentage output obtainable by using intermediate condensers, assuming a transmission line without resistance and without charging current. On this ideal basis they show that about 50 per cent additional kw. can be sent over a line by this means, on the basis of the reasonable values of $\frac{E_T}{E_A} = 0.9$, and $\frac{Z_C}{Z_L} = 0.6$. From equation (42), and the other data given, I calculate that this result is obtained by adding 200 per cent of the original line capacity in condensers. Or, in order to obtain each kilowatt of additional line capacity, it is necessary to add 4 kw. of condenser capacity. Under the different assumptions used in Fig. 22, approximately the same ratio is shown. Here, the authors have assumed no line losses, an infinite bus at the receiver, a very low generator reactance, and they have not stated clearly how they allowed for the important effects of the line charging currents.

Thus, the results of the paper indicate that under practical conditions it will be necessary to install much more than four times as much condenser capacity as there is obtained additional line capacity; and so it does not appear that the scheme of the intermediate condenser station is of great economic value at the present time.

In spite of my feelings that the results they have obtained are not of immediate practical importance, I feel that the authors have performed a great deal of useful work in their study of this important problem, and that their paper will be of great value as a basis for further study.

R. D. Evans: The question of the limiting stable angle is quite involved. The criterion selected was that the system be forcibly displaced slightly from the normal condition for which the mathematical solution of the voltage, power, and circuit conditions were satisfied. In order to determine whether or not the system pulls out at that point one must consider the transient and on account of the inertia and electrical loads one end tends to move more rapidly than the other. The possibility concerning which Mr. Alger is doubtful (if I understand him correctly), is the fact that if the angle is increased slightly the machine that is leading may tend to slow down more rapidly, and therefore to stay in step.

Concerning the question as to the effect of the governor, it is necessary only to point out that when the angle is decreased, more power can be transmitted.

With respect to the second point brought out by Mr. Alger, the amount of condenser kv-a. that has to be added to a system to increase the amount of power which can be transmitted, I do not know the exact basis used for his computations. If one considers the case of a system operating close to the static limit without a condenser and the ratio of the increase in reactive power to the increase in real power and then compares the corresponding conditions with a condenser operating near the static limit, it is true that one will obtain a relatively large increase of reactive kv-a. for each kilowatt increase.

The practical condition, however, is this: the system will be operated appreciably below static limit and under these conditions the increase in condenser capacity for each kilowatt of increased power which can be transmitted is not nearly so large

as indicated by Mr. Alger. Furthermore, the total magnetizing kv-a. required by the system is actually less when supplied by machines which are distributed than when all condensers are at the receiving end. If the means for supplying reactive kv-a. are distributed an increase in the power limit is secured. So, for the practical conditions one can increase the power transmitted and also increase the margin of stability and thus arrive at the best compromise as to the increase of condenser capacity on the system and the amount of power to be transmitted, and in no event will one closely approach the static limits.

R. W. Mackey: (communicated after adjournment) The paper by Messrs. Wagner and Evans covers the cases of the static stability limits of straight-line transmission with one or two intermediate condenser stations, but where the system is more complicated or in the form of a network with condenser stations distributed on the network the mathematical method becomes cumbersome and practically impossible of solution.

The case I have in mind is the 220-kv. interconnection now being carried out in the east between the Philadelphia Electric Company, The Pennsylvania Power & Light Company, and the Public Service Gas & Electric Company of New Jersey.

During the last four months we have developed the mechanical model demonstrated by Mr. Evans for application to the quantitative solution of such complicated systems.

In the above case we were more concerned with the transient stability under short circuit and worst switching conditions than anything else but our solution also gave information as to static conditions.

I should like to elaborate on the methods used but this whole investigation is being prepared in the form of a paper to be presented by Messrs. Bergvall and Robinson.

At this time I mention this as it may be of interest for members to know that we are tackling the more complicated systems and expect to obtain great help from the analogous synchronous mechanical system.

C. F. Wagner: Dr. Terman's remarks regarding the increase in power occasioned by the use of an intermediate condenser station are substantially correct and in accord with our point of view. We concur with his remarks regarding the desirability of low-reactance condensers and quick-response excitation. In interpreting the curves showing the improvement on actual power systems, several facts must be born in mind. These results show the static limit of lines in which the amount of copper was dictated by loads considerably below the static limit, that is, for loads determined by the transient limit. If the static limit were determining, larger conductors would have been chosen for the line without condensers and still larger conductors for the line with condensers. A comparison under these conditions, paying due regard to the increased financial burden occasioned by larger conductors, would have been much more favorable for the intermediate condenser.

Mr. Alger questions our ideas regarding the limiting angle and states that our conclusions seem unreasonable to him. He cannot agree that the inertia has anything at all to do with the maximum angle at which the system can operate. Perhaps a discussion of a simple system consisting of a synchronous generator and synchronous motor with a connecting impedance in which the resistance is equal to the combined reactance of the line and machines, may clear this point. For the first case let the inertia of the generator be extremely large and the inertia of the motor, small. This corresponds to a small motor connected to a large system through an impedance. It is evident then that no action of the motor will be reflected in the main system. The power input into the motor will then increase until the angle reaches 45 deg., beyond which it will decrease. The limiting angle in this case is equal to the impedance angle. This is the more familiar arrangement and one from which the idea that the angle could not exceed the impedance angle was probably derived, but conclusions drawn from this illustration cannot be applied indiscriminately to other cases. Consider now that this synchronous motor is acting as a generator and is feeding power into the large system through such an impedance. Again, any phenomena in the generator will have an inappreciable effect upon the large system, whether it be voltage change or change in phase position of the rotors. With increasing angle the power input into the system will increase until an angle of 45 deg. is reached, beyond which the power will decrease. But what occurs to the output of the generator? This increases continuously even beyond 45 deg., reaching a maximum at 135 deg. While the input into the system decreases beyond 45 deg. the increase in copper loss is more than enough to overcome the decrease in system input. Now the generator responds, not to input into the system, but to its output. The system will be stable up to an angle at which an increase in angle no longer produces an increase in output, which in this case is 135 deg.

It is hoped that this discussion will make more lucid our conception of what occurs when the limiting angle is reached. While this discussion considered only limiting cases in which the inertia of one of the machines was extremely large it should be clear that for machines with more nearly equal inertias the difference in operation is one of degree only. These ideas have been verified by shop tests in which, citing from random, we have been able to obtain angles as large as 140 deg. No particular effort has been made to obtain larger angles.

I am at a loss to understand Mr. Alger's criticism of Fig. 22, when he states that no line losses were included in the calculations and we had not clearly stated how we had "allowed for the important effects of the line charging currents." The development of the formulas presented in the paper were premised on the most general type of circuit including both lumped and distributed constants. The general form of the equations are given in equations (1) and particular reference was made to distributed constants in the paragraph preceding equations (3). Mr. Alger's remarks regarding the efficacy of condensers should be tempered by the same considerations mentioned in the discussion of Dr. Terman and our reply. We do *not* agree with Mr. Alger that the scheme of the intermediate condenser station is not of great economic value at the present time, but on the contrary see wonderful possibility in its utility for the transmission of large blocks of power over great distances.

Synchronous Condensers

BY P. L. ALGER[1]

Member, A. I. E. E.

Synopsis.—*The paper reviews the general characteristics of large synchronous condensers, with particular reference to the possibilities of greater standardization in condenser specifications. Particular emphasis is placed on the question of the ratio of lagging to leading kv-a. capacity, and it is concluded that about 50 per cent lagging capacity is normal, while any important increase in this ratio requires special design of greater size and cost. Attention is called to the advantage to be gained by the use of reactors in place of such oversized condensers, where extra lagging capacity is needed. Separate sections of the paper are devoted to starting and stability characteristics, and to recent improvements in the design of synchronous condensers. Finally, the use of asynchronous condensers is discussed and found to be undesirable.*

* * * * *

I. Object of Paper

The large amounts of leading kv-a. required by modern power systems are most economically provided by means of synchronous condensers, and so the numbers and unit sizes of these machines have steadily increased in recent years. Thus, in 1925 two 40,000-kv-a., and this year the first of three 50,000-kv-a. condensers were placed in service on the Pacific Coast, while upwards of 35 others of sizes above 1000 kv-a. were built in the United States during 1926. Their continually increasing importance makes it desirable to simplify and standardize specifications for them as much as possible by eliminating unnecessary restrictions on their design. This paper is devoted to the description of some of these possibilities, and to the review of present practises in condenser design.

II. Principal Characteristics of Synchronous Condensers

The outstanding advantage of the synchronous condenser from an operating point of view, as compared with other means of supplying corrective kv-a., is the flexibility of its control. Once the machine is connected to the system, the reactive kv-a. it supplies can be varied continuously over the entire range from 50 per cent or more lagging to full leading kv-a., by simple adjustment of its field current. The adjustment can readily be made fully automatic, and so any desired condition, such as constancy of voltage or of power factor at a given point on the system, can be maintained.[2] This ease of adjustment also enables machines of very large size to be put on or taken off the system without appreciable disturbance. Thus, the economic advantages of large sizes can be fully realized with synchronous condensers.

Also, from the manufacturer's point of view, the synchronous condenser has an outstanding advantage over other rotating machines due to the fact that it neither drives nor is driven by any other apparatus. This permits a single, most economical, speed to be used for any given size, which, in turn, greatly helps standardization. Besides, the torque required being merely that to hold the rotor in step, the usual stability limitations of synchronous machines are lifted, and consequently very high current loadings can be employed. All these things contribute to the attainment of low costs. On the other hand, the low initial cost of the condenser itself and the small amount of associated equipment required combine to make the operating cost of the power losses an abnormally high proportion of the whole. On this account, special emphasis is placed on the attainment of low losses in synchronous condensers, and this factor tends to increase the initial cost.

III. Possibilities of Standardization of Condenser Design

Ideal conditions for standardization combined with progress, exist when specifications are so drawn as to impose the least possible number of fixed requirements, and when contracts are awarded on the basis of the best performance on the non-fixed requirements. In this way, each manufacturer is given maximum freedom for the use of his available developments and for the play of his initiative. When more requirements than those absolutely necessary are laid down, all manufacturers are forced to do some things in the same way, with consequent inconvenience and increased developmental costs for some of them. Synchronous condensers much more nearly approach this ideal condition than most other types of rotating machines, and yet it seems that further progress in this direction can be made.

Aside from the restrictions imposed by the system frequency and by the method of rating employed, there are four variables that the purchaser may specify in describing a synchronous condenser. These are:

1. Leading kv-a. capacity, or rating,
2. Number of poles, or speed,
3. Voltage,
4. Ratio of lagging to leading kv-a. capacity.

The first of these is the fundamental variable that determines the size of the machine, so that the only possibility of standardization here is in the limitation of the number of ratings called for. Present practise in this respect is quite satisfactory, as the list of usual

1. A-c. Engineering Dept., General Electric Co., Schenectady, N. Y.

2. Woodruff, "Principles of Electric Power Transmission," p. 153.

Presented at the Pacific Coast Convention of the A. I. E. E., Del Monte, Calif., September 13-16, 1927.

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ratings given in the first column of Table I has increments of at least 20 per cent, and intermediate ratings are seldom called for.

It is not desirable for the purchaser to specify the speed, as this limits the manufacturer's possibilities, and usually handicaps one more than another. The natural desire to improve his designs, and the economic urge of competition will cause each manufacturer to select the most economical speed for each machine, and the ultimate user has, therefore, nothing to gain by insisting on any particular value for it. As high-speed machines are lighter and more efficient than low-speed machines up to the points at which mechanical stresses and windage losses become limiting, it follows that synchronous condensers are normally built for high speeds. At the present time the speeds listed in Table I are customary, but the ratings at which the speed is changed vary slightly among different manufacturers. Usually, machines are guaranteed for 25 per cent overspeed.

Sometimes condensers are placed in substations in residential districts where quiet operation is essential, and this has been thought to require machines of lower than standard speeds. However, it is possible to so enclose a high-speed condenser as to make it satisfactorily quiet at less cost, and with better performance than can be obtained by using a speed below standard.

TABLE I
MOST ECONOMICAL SPEEDS AND VOLTAGES OF LARGE SYNCHRONOUS CONDENSERS

Kv-a rating	60 cycle, r. p. m.	Voltage
500	1,200	2,400/4,150
750	1,200	2,400/4,150
1,000	1,200	2,400/4,150
1,500	1,200	2,400/4,150
2,000	900	2,400/4,150
3,000	900	2,400/4,150
4,000	900	2,400/4,150
5,000	900	6,900 or 11,500
7,500	900	6,900 or 11,500
10,000	900	6,900 or 11,500
15,000	720 or 900	11,500 or 13,800
20,000	720	11,500 or 13.800
25,000	600 or 720	11,500 or 13,800
30,000	600	13,800
40,000	600	13,800
50,000	600	13,800

For large sizes, it is often economical to use a completely closed system of ventilation with water coolers, as described in section VIII. If this is not desired, it is still possible to reduce the noise to a very small amount by using a standard enclosed machine with the addition of an air discharge chimney on top. Felt covered baffles can be so placed in this chimney as to practically eliminate the high pitched part of the noise without impeding the air flow to an important extent.

The voltage situation is not so simple as that of the speed, as there are so many different system voltages employed. However, the recent conferences on the subject, at New York and Niagara Falls (culminating in the new N. E. L. A. table of preferred standard voltages), give promise of some improvement. Also, as synchronous condensers are frequently provided with their own transformers or are fed from special tertiary transformer windings, it is often possible to choose the voltage that gives the most economical design. If the condenser voltage is too high, excessive insulation costs, and extra losses due to the large slots required will result; while if it is too low, excessive costs for the high current-carrying capacity and extra losses due to eddy currents in the massive conductors will arise. Hence, there is a most economical voltage for every rating, values of which are indicated in the third column of Table I.

In practise, the cost advantages of standardization are greater than those secured by selecting the ideally correct voltage, so that only the standard voltages nearest the ideal value are given in the table. It is customary to make the smaller machines suitable for either Y or delta connection.

The remaining variable is the ratio of lagging to leading kv-a. capacity. When a condenser is to be used solely for power-factor correction, to compensate for the lagging kv-a. of an industrial load, the lagging kv-a. capacity is of no direct interest, and so, in these cases, it is rightly left for the manufacturer to settle. As a value of the ratio not far from 0.5 gives the most economical design for leading power-factor operation, this is the value characteristic of most standard condensers. However, when condensers are to be used for voltage regulation, a considerable lagging kv-a. capacity is useful to hold the voltage down at light loads, and so, purchasers frequently specify a value of unity for this ratio. This imposes a considerable handicap on the designer and requires a special machine so that it is desirable to find some other way to obtain the desired results. It is worth while to study this question at some length, so the effects on design of varying this lag/lead ratio will first be described, and then methods of securing the desired operating results with normal condensers will be considered.

IV. Lagging Kv-a. Capacity Secured by Changes in Condenser Design

The line current of a synchronous condenser is always equal to the difference between the voltage induced by its field and the impressed voltage divided by its synchronous reactance and corrected for saturation. Over-excitation of the field produces a leading current, and under-excitation produces a lagging current. The maximum possible lagging current occurs with zero field current, and is therefore equal to the line voltage divided by the synchronous reactance. While stable operation with a small reversed field excitation is possible, the trouble of providing for this reversal and the attendant increased likelihood of the condenser's falling out of synchronism make it inadvisable. For

our purposes, therefore, the ratio of maximum lagging to normal leading kv-a. capacity of a synchronous condenser may be taken equal to the reciprocal of the per cent synchronous reactance, or to:

$$\text{Per cent maximum lagging kv-a.} = \frac{100}{X_s} = 100\ Y_s \qquad (1)$$

As lagging kv-a. are supplied when the field is under-excited, under this condition, the saturation of the magnetic circuit is slight and may be neglected. On the other hand, the leading kv-a. are supplied when the field is over-excited, a condition in which saturation of the magnetic circuit is pronounced.

If the ratio of the actual field excitation to the no-load air-gap excitation is represented by F, the per cent leading kv-a. is determined by the equation:

$$\text{Per cent leading kv-a.} < 100\ (F - 1)\ Y_s \qquad (2)$$

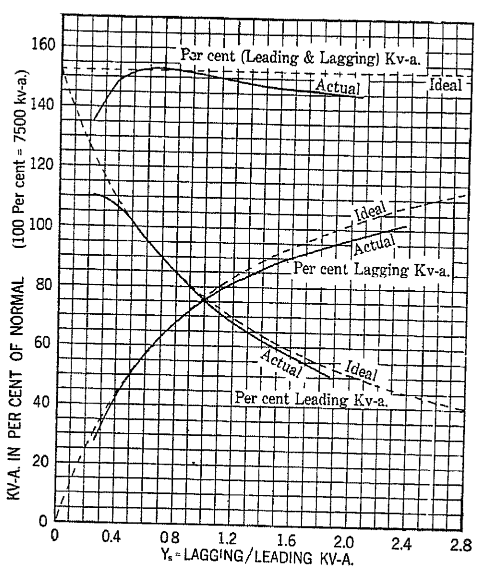

Fig. 1—Relative Leading and Lagging Kv-a. Capacities of a 7500-Kv-a., 900-Rev. per Min. Synchronous Condenser with Varying Air-Gap Lengths

Without saturation, the inequality sign becomes an equality sign, so that (2) reduces to (1), if F is made equal to zero. Adding (1) and (2), the sum of the leading and lagging kv-a. is found to be,

$$\text{Per cent (leading + lagging kv-a.)} < 100\ F\ Y_s$$

$$= 100 \frac{\text{rated field current}}{\text{S. C. field current}} \qquad (3)$$

Equation (3) indicates that the sum of the leading and lagging kv-a. capacities of a given machine is nearly independent of the no-load excitation. At full leading kv-a., (2) becomes equal to unity, so that the relation between F and Y_s is found to be,

$$\frac{\text{No-load air-gap field current}}{\text{Full-load field current}} = \frac{1}{F} < \frac{Y_s}{1 + Y_s} \qquad (4)$$

Equations (1), (2), and (3) are plotted in Fig. 1 as functions of Y_s. The dotted curves show the ideal conditions in the absence of saturation, while the solid curves show the actual conditions for a particular 7500-kv-a., 900-rev. per. min. condenser with different lengths of air-gap but with constant field excitation. The figure clearly indicates the sacrifice in leading kv-a. capacity necessary to secure greater lagging kv-a. If, instead of merely varying the air-gap, keeping the same stator, the entire design is changed always to keep the current carrying capacity of the stator winding just adequate for the maximum kv-a., slightly greater output can be obtained. For example, at a 100 per cent ratio of lagging to leading kv-a., a complete redesign will enable 83 per cent of normal leading kv-a. to be obtained as compared with only 75 per cent when the air-gap alone is changed. The more extensive changes, however, make the machine more special and require additional developmental charges, so that they are not always of economic advantage.

These results may be summarized by the statement that a synchronous condenser of a given size and cost may be designed to give any one of the four following combinations of leading and lagging kv-a. capacities:

Standard................	100% leading,	50% lagging
Semi-standard............	90% leading,	65% lagging
Semi-standard............	75% leading,	75% lagging
Special..................	83% leading,	83% lagging

Of course, these figures are only approximate, and the use of the nearest standard ratings, and of available design parts, will give rise to considerable variations. Nevertheless, they show the true effects, over a standard line of condensers, of different specifications for Y_s.

It is not worthwhile here to study the detail design differences between machines with various values of Y_s, but it is desirable to clearly realize the reasons for the reduction of rating that accompanies an increase in it. If a standard condenser is to be given an increased lagging capacity, without increase in size or cost, its air-gap must be lengthened. This entails a corresponding reduction in winding space on either rotor or stator and increases the field leakage, though it slightly decreases the armature leakage reactance and the pole-face losses. On the other hand, it is not practical to secure an increased leading kv-a. rating by reducing the lagging capacity below about 50 per cent because the air-gap excitation is already small compared with the total, and even a large reduction in the air-gap length will only make a slight gain. Further, when the gap is very small, excessive increases in armature reactance and in pole-face losses occur.

These facts have long been appreciated by designers,[3] but it is believed that they are not generally understood and that they deserve greater emphasis than they have heretofore received.

So far, we have merely shown that there is a definite decrease in kv-a. rating of a given machine if Y_s is increased. There is also a distinct handicap in losses

3. Reference Nos. 6, 9.

in leading kv-a. operation imposed by a wide departure from the normal value of Y_s. In Fig. 2, for example, there are shown the per cent losses of the same 7500-kv-a., 900-rev. per. min., synchronous condenser used in making Fig. 1. The curves show the expected full-load losses with different air-gaps, but the same stator, for both lagging and leading operation, as percentages of the kv-a. under each condition. These values of kv-a. are shown by the solid curves of Fig. 1. Redesigning the entire machine to obtain the best possible design for each length of air-gap does not materially reduce the losses, as shown by the points plotted at 100 per cent Y_s.

We, therefore, conclude that it is desirable to keep the value of Y_s between 0.5 and 0.6 for a standard line of synchronous condensers. Wide departures from this range increase both costs and losses and so cannot be considered standard, and keeping closely to it will greatly facilitate standardization and will tend to further reduce costs and improve performance.

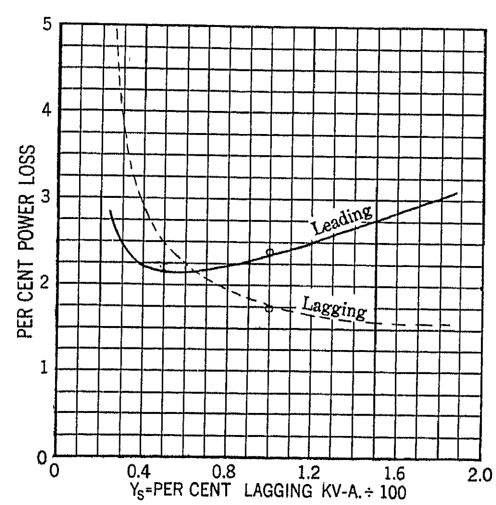

Fig. 2—Relative Full-Load Losses of a 7500-Kv-a., 900-Rev. Per Min. Synchronous Condenser with Varying Air-Gap Lengths

The desirability of this fixation of the value of Y_s from the cost and efficiency viewpoints being established, it remains to consider it from the operating viewpoint.

V. Other Methods of Securing Lagging Kv-a. Capacity

There are four principal methods of securing lagging kv-a. capacity without departing from normal condenser designs:

1. By reconnection of the condenser windings,
2. By raising the condenser voltage by means of transformer taps,
3. By use of reactors, and
4. By reduction of the system voltage.

The simplest general method of reconnection is to divide each phase in halves and connect unlike halves in series for lagging power-factor operation. On three phase, this is equivalent to increasing the voltage in the ratio of $2/\sqrt{3}$, and so it raises the lagging capacity to 4/3 of its normal value. However, unless rather complicated internal connections are made, the scheme considerably increases the short-circuit core losses.[4] In special cases, it is possible to change the number of circuits, and it is always possible to bring out taps from the winding in such a way that some of the armature coils can be cut out, with similar effects. These schemes however, all involve rather expensive switching arrangements, and they are not conveniently adaptable to automatic operation; also, they all result in increased losses per kv-a., so that from this point of view they are not attractive. Some of the methods are desirable for use in special cases, such as when a single machine is to be operated at different times on circuits of different frequencies, but they cannot be recommended for standard practise. At best, it is not practicable to double the lagging kv-a. capacity of a condenser by such means, so that they cannot completely solve the problem.

The recent developments in tap changing transformers[5] at first sight give promise of a solution by enabling the voltage to be varied at will over a wide range, without opening the circuit. However, on closer scrutiny, this possibility too is seen to be chimerical. In the first place, the tap changing apparatus is quite expensive, and the cost of the condenser is considerably increased by the necessity for insulating it for the highest voltage used. These extra costs alone are about the same as the extra cost of making the original condenser good for full-lagging capacity, and, in the second place, the losses in lagging power-factor operation are considerably increased by this arrangement as compared with the latter scheme.

In Fig. 3 there are shown curves of leading and lagging kv-a. capacity and per cent losses as functions of the impressed voltage, for the same 7500-kv-a., 900-rev. per. min., 11,000-volt condenser used in the previous figures. A voltage of about 130 per cent is required to give 90 per cent of rated kv-a. in lagging operation, at which point the losses are 2.2 per cent as compared with only 1.6 per cent for the oversized condenser built with a large enough air-gap to give the same lagging capacity (Fig. 2 at $Y_s = 1.55$). The curves show that no appreciable increase in leading kv-a. capacity can be secured by reducing the voltage, so that there is no incidental gain from this source to offset the disadvantages in lagging operation. We conclude, therefore, that the voltage regulation scheme is not of value for our purpose.

There remains the scheme of supplementing the deficient lagging kv-a. capacity of the standard syn-

4. Reference No. 6 and Q. Graham, *M. M. F. Wave of Polyphase Windings*, Journal A. I. E. E., February 1927, p. 118.

5. A. Palme, *Application and Design of Load Ratio-Control Equipment*, presented at the Regional Meeting of District No. 1 of the A. I. E. E., Pittsfield, Mass., May 25-28, 1927.

chronous condenser by the addition of parallel-connected reactors. As high-voltage air core reactors can now be built at costs per kv-a. which are about half those of synchronous condensers and with total losses of only about 1 per cent, this idea looks promising. The obvious objection to it is that it requires additional apparatus with suitable control and extra floor space.

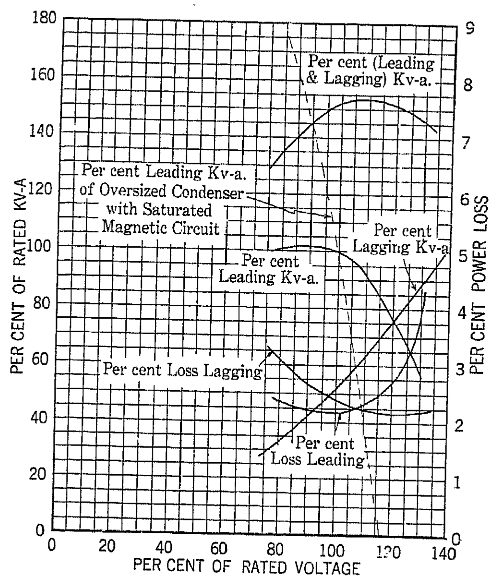

FIG. 3—RELATIVE CHARACTERISTICS OF A 7500-KV-A., 900-REV. PER MIN. SYNCHRONOUS CONDENSER IN VARIABLE VOLTAGE OPERATION

Furthermore, unless the reactors are to be thrown on the line all in one unit, expensive sectionalizing switches are required. Thus, the complete equipment is more expensive than a single oversized condenser designed for full lagging capacity.

The comparison of kv-a. ratings obtainable for the same cost, given in part IV, show that a standard condenser has 4/3 the leading kv-a. and half the lagging kv-a. ratings of an equivalent special condenser with 100 per cent lagging capacity. Taking the cost per leading kv-a. of the standard condenser as 1, and that of a reactor as ½, the total cost of the standard condenser plus sufficient reactors to give full lagging capacity is 1.25, while the cost of the special condenser is 1.33. These figures are rough, and they will be changed considerably by the addition of the extra equipment necessary, but they show that the costs of the two schemes are not widely different.

In the long run, however, the capital cost of the reactor scheme may prove to be the lower, for lagging kv-a. are principally required when a system is lightly loaded, in order to keep down the no-load voltage. Over a period of time, as the system load increases, the times of light load become shorter, and the minimum load becomes greater, so that less lagging kv-a. are required, and the demand comes to be for leading kv-a. capacity to hold the voltage up during overloads. Hence in some cases, it should be economical to install reactors alone when a transmission line is first built, later to add standard condensers, and finally to take the reactors away altogether for use at some other place, or for sale.

One of the chief reasons for specifying condensers with large lagging capacities seems to be the desire to make ample provision for the lagging kv-a. requirements in case these are greater than estimated. In such cases, it is often found that the extra lagging capacity is not actually needed. If, therefore, it is realized that additional lagging kv-a. can be secured at any later time on an economical basis by adding reactors, it will be possible to purchase initially condensers that have a lagging kv-a. capacity only equal to the estimated requirements, for which standard machines are usually adequate.

From the point of view of power losses, too, the reactor scheme may be attractive. Fig. 4 shows the total losses in per cent of kv-a. output for the combination of the standard 7500-kv-a. condenser used in the previous figures with sufficient air-core reactors to give a total of 100 per cent lagging capacity; together with a similar curve for a larger condenser built with a sufficient air-gap to give it 7500 kv-a. capacity on both leading and lagging operation. At light lagging loads the smaller condenser is slightly more efficient, while if the condenser is shut down and the reactors alone are used at light loads, a large saving in losses results. At medium loads the larger condenser has a little lower

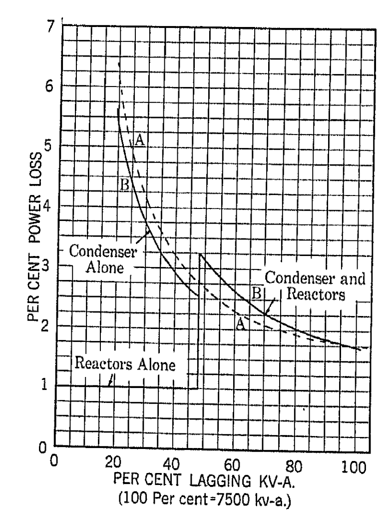

FIG. 4—RELATIVE POWER LOSSES IN LAGGING KV-A. GENERATION

A. Special synchronous condenser with 100 per cent lagging kv-a. capacity

B. Standard synchronous condenser with 52 per cent lagging kv-a. capacity and 48 per cent kv-a. of reactors

losses, but at full lagging kv-a. the combined unit gives better results. The variations are sufficiently small, however, to make the balance depend upon the operating schedules.

All these methods of securing extra lagging capacity involve extra cost and losses, so that it is desirable to avoid the difficulties by merely reducing the system

voltage. This reduces the leading kv-a. supplied by the transmission line capacity, and increases the lagging kv-a. due to the line reactance, thus greatly decreasing the lagging requirements. The voltage reduction may be made temporarily during a time of light load. In general, a system design that gives permanently large lagging kv-a. requirements is not the most economical.

VI. Methods of Starting Synchronous Condensers

It is standard practise to provide synchronous condensers with amortisseur windings and to start them from a low-voltage transformer tap or from an auto-transformer. This method of starting is readily adaptable to automatic operation, and the equipment required costs less than a starting motor with its control and the necessary synchronizing apparatus. Unless a source of low voltage for the starting motor is already available, an extra transformer must be provided for it, and in this case the cost is very much greater; also, automatic operation with a starting motor is more difficult. The only apparent advantage of a starting motor is the possibility of securing a lower reactive component of the initial starting current by its means.

As the starting kv-a. required by a standard condenser is only about 30 per cent of normal, and this can be reduced to about 20 per cent by adding oil pressure starting equipment, it does not seem that the use of a starting motor is ever necessary on this account. However, in rare cases it may be desirable occasionally to use a condenser for line charging or for testing a transmission line, and a starting motor will then be necessary. If a condenser is to be operated on unbalanced voltages or under other conditions where a very low-resistance amortisseur winding is needed, the condenser's starting characteristics will be poor and a starting motor will be desirable.

In order to keep down the induced field voltage, it is customary to short circuit the field through a resistor during the starting period. The condenser will then come up to full speed on the tap voltage, and field is applied before it is thrown over to full voltage. When the change to full voltage is made, the field current being kept constant, the kv-a. drawn from the line will change suddenly by an amount depending on the value of field current used. Let T represent the ratio of tap to line voltage, Y_s the ratio of lagging to leading kv-a. capacity, and E the ratio of the field current during synchronizing to the no-load field current. Then the leading kv-a., drawn from the line on the tap, are represented by:

$$T\,(E - T)\,Y_s$$

and the leading kv-a. on full voltage are:

$$(E - 1)\,Y_s$$

For minimum shock to the system, these two must be equal, whence we find the best value of field current to use on synchronizing is:

$$E = T + 1 \qquad (5)$$

which gives leading kv-a. equal to $T\,Y_s$

As a standard condenser usually has a no-load field current equal to about one-third of its full-load field current, and as the tap voltage used for starting is usually not over 30 per cent, equation (5) shows that the best value of field current for synchronizing is a little less than 40 per cent of its rated value.

In practise it is convenient for the operator to determine the best value of field current by taking two V curves on the condenser, one at full voltage and one on the starting tap, reading the current input on the line side of the compensator. Then, as indicated in Fig. 5, it is a simple matter to prolong the leading branches of the two V curves until they intersect, and this will give the desired field current. The magnetizing kv-a. of the compensator are usually large enough to make the determination by readings on the low side of the compensator considerably in error, as indicated by the dotted line in Fig. 5.

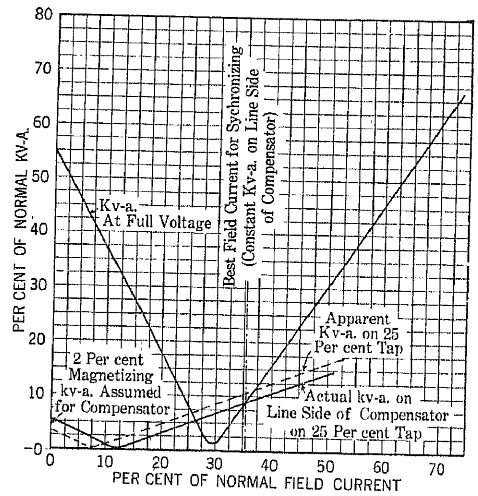

Fig. 5—Voltage Curves of a 7500-Kv-a. Synchronous Condenser

Showing method of determining best field current for synchronizing

Previous articles dealing with this question have sometimes recommended the field current value corresponding to the same armature current on the leading branch of the low-voltage V curve and on the lagging branch of the full-voltage curve. In this case, the change from leading to lagging kv-a. will give an appreciable shock to the system, as the system excitation must change immediately in the opposite direction. As there is practically no torque exerted by the condenser, the phase position of the pole with respect to the armature current is nearly the same for all values of excitation, and, therefore, whatever value of field current is used, there should be very little shock to the condenser itself.

Since the transition from the tap to full voltage can be made without requiring any appreciable change in the phase position of the rotor or in the total kv-a. drawn from the line, it is not of great importance whether the circuit is momentarily opened during the

transfer or not. If the circuit is held open for an unnecessarily long time, amounting to a second or more, the rotor will fall back in phase and a mechanical shock will be experienced on reclosing.

Instead of first closing the field through a resistor and later opening the resistor circuit and applying field voltage, it is often convenient to simply close the field through the direct connected exciter at the beginning, and allow the machine to synchronize itself on the tap voltage. In this case, the exciter must build up so slowly that the direct component of the field current does not become important until the condenser is at speed. If the exciter builds up too rapidly, the machine will not come up to full speed. The remedies in such a case are either to cut in more resistance in the exciter field circuit, or to use a higher tap voltage for starting.

VII. Stability of Synchronous Condensers

There are two aspects of the stability question as it relates to synchronous condensers, the first dealing with the stabilizing effect of a condenser on the system voltage, and the second dealing with the ability of the

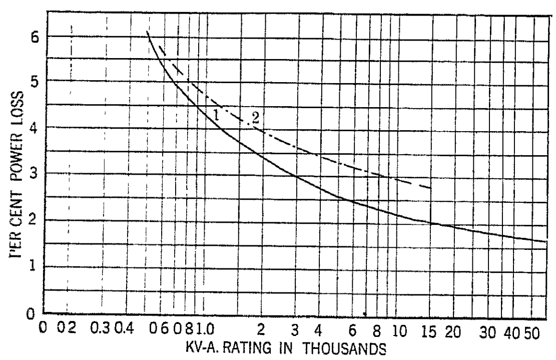

Fig. 6—Power Losses of Synchronous Condensers
Corresponding to usual manufactures guarantees

condenser to stay in synchronism during system disturbances. These will be considered in turn.

A dead system load, made up of lamps, resistors, reactors and so forth, is characterized by a constant ratio between its voltage and current. If the voltage rises or falls, the current does likewise in an equal ratio, without change of power factor. A live load, made up of synchronous and induction motors, is characterized by a constant kilowatt demand, independent of voltage, so that in this case the power component of current rises if the voltage falls, and vice versa. With a dead load, therefore, a fall in voltage results in a decrease in line drop, while with a live load a fall in voltage gives an increased line drop. The former is always a stable, and the latter may be an unstable condition.

For good system stability, it is necessary to counteract the effects of a live load by adding equipment that will give a rapid decrease in the line drop whenever the voltage falls. A static condenser is of no use for this purpose, as the current falls with the voltage, and thus the voltage rise it produces falls also, increasing the instability. An induction voltage regulator can be used, but its effect is secured by the action of its control mechanism, and so is not immediate. On the other hand, a synchronous condenser fulfils the desired conditions, as it gives an increased leading current when the voltage falls, and vice versa. The action in this case is immediate, as the field excitation is always equal to the sum of the values required to produce the voltage and the armature current, and any decrease in one results in an equivalent increase in the other. This property of the synchronous condenser is of the greatest importance in problems of system stability.

By automatic voltage regulator control of the condenser field current, a delayed action of the same kind, that further increases the leading current when the voltage falls, can be secured, and, by using a quick-response excitation system with a proper voltage regulator, the time delay in securing the additional effect can be made very short. Or, by designing the condenser with a strongly saturated magnetic circuit at normal voltage, a large amount of field excitation will be released by a fall in voltage, and made available for the production of additional leading armature current. As Fig. 3 indicates, a normal condenser gives a slight increase in total leading kv-a. as the voltage falls, while a saturated machine gives a large increase. Thus, by the use of a saturated design the armature current may be made to instantaneously increase much more rapidly than the voltage decreases, even with a fixed field current. It is probable that these two ideas of a quick response excitation system and a saturated magnetic circuit will prove to be very useful in solving the future stability problems of large systems.

A standard synchronous condenser with about 50 per cent lagging kv-a. capacity has a pull-out torque of about 175 per cent of its rated kv-a., with full excitation. At no-load, the pull-out torque is reduced to about 75 per cent, and even with zero field current, corresponding to full lagging kv-a., it still has a pull-out torque of about 20 per cent of its rating. A condenser designed for 100 per cent lagging capacity has corresponding pull-out torque values of about 225, 125, and 30 per cent. A standard condenser of 5000 kv-a., or above, also has a value of $W R^2$ equal to:

$$W R^2 = (6 \text{ to } 8)\ (\text{kv-a.}) \left(\frac{1000}{\text{rev. per. min.}}\right)^2 \text{lb. ft. squared} \tag{6}$$

The familiar equation for the torque required to produce angular acceleration in a rotating mass can now be applied to determine what rate of change of frequency can occur without the condenser falling out of synchronism. This equation is:

$$\frac{W R^2}{g} \ \frac{d\,w}{d\,t} = \text{torque,} \tag{7}$$

where the moment of inertia in pound-feet-seconds squared is:

$$\frac{W R^2}{g} = \left(\frac{7}{32.2}\right) (\text{kv-a.}) \left(\frac{1000}{\text{rev. per. min.}}\right)^2, \quad \text{approximately,} \quad (8)$$

the angular acceleration in radians per sec. squared is:

$$\frac{d\,w}{d\,t} = w\left(\frac{d\,w}{w\,d\,t}\right) = w\,\frac{d\,f}{f\,d\,t}$$

$$= \left(\frac{2\,\pi}{60}\right) (\text{rev. per. min.}) \frac{d\,f}{f\,d\,t}, \quad (9)$$

and the torque in foot-pounds is:

$$\text{Torque} = (0.2 \text{ to } 1.75) \frac{7040 \text{ (kv-a.)}}{\text{rev. per. min.}} \quad (10)$$

Substituting these expressions in (7), we find the allowable rate of change of frequency for a standard condenser to be:

$$\frac{d\,f}{f\,d\,t} = 0.06 \text{ for zero field excitation}$$

$$= 0.23 \text{ for no-load excitation}$$

$$= 0.55 \text{ for full-load excitation} \quad (11)$$

This means that the frequency could be changed 55 per cent per sec. without causing a standard condenser operating at rated field excitation to fall out of step, *provided the voltages at its terminals were held absolutely constant and balanced.* In practise, a system disturbance usually both lowers and unbalances the voltage, so the actually allowable rate of frequency change is much less.

The torque developed varies as the square of the voltage with no field excitation (full lagging operation), and just a little faster than the first power of the voltage at normal excitation (full leading operation). If one line terminal is opened, the condenser operates single-phase, and has a pull-out torque about 70 per cent of its value at the same voltage three-phase. If, however, the voltage between two terminals falls very far, corresponding to a short circuit between lines, the short-circuited phase acts as a generator feeding power to the fault, and the pull-out torque is reduced still more. Also, the existence of reactance in the lines and transformers may greatly reduce the pull-out torque. On the whole, therefore, taking into account these factors and remembering that the maximum torque of a synchronous machine is not fully available, due to the hunting that always occurs on disturbances, it is probable that not more than 10 per cent of the rate of frequency change given by (11) is permissible.

Our conclusion is that a condenser operating at rated field current will stay in step during system disturbances if the frequency does not change more rapidly than 5 per cent per sec.; and at zero field current it will stay in step during frequency changes up to ½ per cent per sec. If it falls out of step when the field excitation is very small, the condenser will behave like an induction motor and will come right back into step after the disturbance is over, while at large excitations, it will come to rest and must be restarted; hence, the lessened stability of a condenser at reduced excitations is not of particular importance. On the basis of these figures, it seems that standard condensers have ample synchronizing power for ordinary applications and that no weight need be attached to this factor in writing condenser specifications.

VIII. Recent Improvements in Condenser Design

Designers are always striving to make more efficient, cooler, and more reliable machines without increasing the cost, and the results of their efforts should be recorded at intervals. There are several recent improvements in condenser design that seem worth presentation here.

The design of amortisseur windings, especially the end rings, has always presented a serious problem on large high-speed machines, as the support of the projecting bars and rings has proved mechanically difficult. Furthermore, the presence of a complete end ring has been very inconvenient in taking down and reassembling the poles. By simply omitting any end-ring connection between poles, the amortisseur winding bars can be shortened, and the ring segment placed close to the pole piece punchings. The expansion of the bars due to heating during starting is taken care of by leaving a small axial clearance between the rings and the pole pieces. This gives a very happy solution to the problem, as it avoids all mechanical difficulties and dangers from overheating of the exposed bars, and greatly facilitates assembly. Most advances in the art bring complications in their train, and it is therefore extremely pleasant to be able to record one that simplifies the design instead. Fig. 7 illustrates this construction.

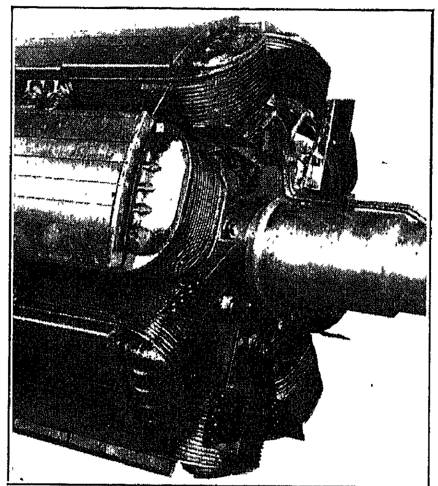

Fig. 7—Rotor of 7500-Kv-a., 900-Rev. Per Min. Synchronous Condenser
Showing open amortisseur winding and finned field coils

Fig. 7 shows the rotor of the same 7500 kv-a., 900 rev. per. min. synchronous condenser referred to in the previous discussions, on which this simplified amortisseur winding construction was used. The deterrent to the use of this scheme heretofore has been the thought that it would give unsatisfactory starting characteristics. The machine shown, and many others of different sizes, have been built in this way, however, without any important difficulties from this source being experienced.

Another recent improvement in rotor design consists of the addition of fins to the ends of the field winding, as illustrated in Fig. 7. These fins are made by simply projecting every second or third turn of the field coil during winding. They give an increased area for cooling on the ends, where it is most effective, and so reduce the field temperature.

In the design of the stator, improvements have taken the form of simpler and stronger mechanical construction by the use of steel plates welded together instead of castings, and in improved arrangements for ventilation. Fig. 8 shows a 10-pole, 20,000-kv-a., 720-rev. per. min., 11,000-volt, synchronous condenser recently built.

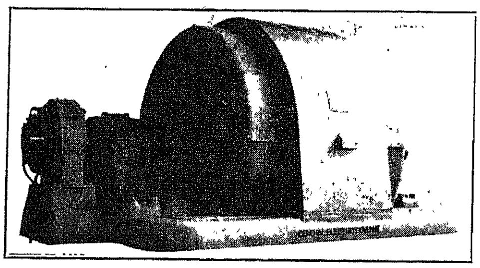

FIG. 8—20,000-KV-A., 720-REV. PER MIN., 11,000-VOLT SYNCHRONOUS CONDENSER
Showing steel plate frame

The welded frame is much lighter than an equivalent casting, and is more easily modified to meet special requirements.

A strong tendency to the use of closed systems of ventilation for large rotating machines, including condensers, has been recently observed. The addition of the necessary enclosing features and water coolers adds about 10 per cent to the first cost of the condenser itself, but it reduces noise to a very small amount, and it is found to give much longer insulation life. The number of cubic feet of ventilating air passing through an open machine is so great that astonishing amounts of dirt can collect on the windings in a short time. For every kilowatt of loss, a machine requires about 100 cu. ft. of cooling air per min., or, on the basis of 8000 hrs. of operation annually, about 50,000,000 cu. ft. each year.

The air found in ordinary buildings usually contains between 0.02 and 0.2 lb. of dust per 1,000,000 cu. ft.,[6] and we may take 0.03 as representing reasonably good conditions. If 10 per cent of the dust in the ventilating air is deposited as it passes through the machine, then 0.15 lb. are deposited annually for each kilowatt of loss. Most large condensers have sufficient cooling air to provide for losses equal to 3 per cent of the rating, so that this means about 4½ lb. dirt per 1000 kv-a. of rating. On a 50,000-kv-a. condenser, this gives a total of over 200 lb. of dirt deposited annually.

6. Margaret Ingels, "How Dusty is Air," *Jl. Am. Soc. of Heating and Ventilating Engineers*, Vol. 31, pp. 415-418, Aug., 1925.

The presence of dirt on the windings and in the air ducts increases, of course, both the temperature rise and the fire risk, so that the use of a closed system of ventilation prevents deterioration of the insulation and provides valuable insurance. These advantages sufficiently explain why the 50,000-kv-a. condensers recently built have been provided with closed system ventilation and water coolers. There is no doubt that an increasing percentage of large machines will be built in this way in the future.

Last, but not least, steady reductions in the losses of synchronous condensers have been going on. In Fig. 6, the usually guaranteed losses of standard condensers of voltages and speeds as given in Table I are shown in comparison with those existing four years ago. Of course, considerable variations from the curve values occur due to the special conditions in each case; nevertheless, the curve can be relied upon for preliminary calculations of the cost of condenser losses in projected installations.

These reduced losses have been obtained by using better proportions in design, so that there is a good balance between the several items of loss, by using better grades of steel, and by employing effective winding transpositions to avoid eddy-current losses. As these features result in more expensive machines than necessary from an operating viewpoint alone, it is important that specifications for individual machines give the value that is to be assigned to savings in losses.

IX. ASYNCHRONOUS CONDENSERS

It is possible to secure a very flexible and stable machine that will give a wide range of leading or lagging kv-a. by exciting a slipring induction machine from a direct connected a-c. exciter. Such a machine will operate at a very small slip that varies with the losses, the sum of the speed and excitation frequencies beings always equal to the line frequency. Hence, it has extremely good stability and will not fall out of step on system disturbances. With excitation in one direction, it gives leading kv-a., and with reversed excitation it gives lagging kv-a., the limits in both directions being set by exciter capacity and heating.

While this type of machine has found fairly extensive use abroad, it does not seem desirable for use in the United States, for, the rotor winding must be distributed in many slots, thus greatly reducing its current carrying capacity, and so the size and cost for leading

power-factor operation are much in excess of those of a corresponding synchronous condenser. Also, in order to partially overcome this handicap, it must have a small air-gap, and a large number of stator slots, which increase both losses and cost.

Its two advantages of extra stability and extra lagging kv-a. capacity are not important here. As pointed out in section VII, the usual standard condensers appear to have ample stability for ordinary applications. This can be attributed to the short time settings of the protective relays generally used in this country, which cut off faults before other machines are noticeably affected. Without protective relays, or with time settings of five sec. or more, the stability of synchronous condensers may become a limiting feature. As indicated above, the costs of synchronous machines with lagging capacities up to 100 per cent of the rating are much less than those of equivalent asynchronous machines.

Finally, the important advantage of synchronous condensers in stabilizing the voltage, discussed in section VII, is lost with the simplest form of asynchronous condenser, which has its a-c. exciter fed from a transformer connected to the main lines. For, in such a machine, the exciting current decreases proportionally to the line voltage, and so the leading current decreases also, making the apparatus equivalent to a static condenser only. This defect can be overcome by providing an auxiliary motor-driven synchronous generator to feed the exciter, at some extra expense, when the machine becomes equivalent to an unsaturated synchronous condenser.

X. Conclusions

From this discussion, several fairly definite conclusions can be drawn. These may be listed as follows:

1. The most economical speeds and voltages for synchronous condensers are approximately those listed in Table I. If quiet operation is important, it should be secured by enclosing features rather than by resorting to lower speeds.

2. Standard synchronous condensers have ratios of lagging to leading kv-a. capacity of approximately 0.5. To require a ratio of unity means an increase in size of about 25 per cent above standard, together with a slight sacrifice in efficiency.

3. To obtain greater lagging kv-a. capacity reconnection, or variable voltage operation of synchronous condensers is not generally desirable, but may be justified in special cases.

4. The use of reactors to supplement the lagging kv-a. capacity of standard synchronous condensers offers many advantages, and may be generally preferable to the use of special condensers with large lagging capacities.

5. The standard method of starting synchronous condensers as induction machines on reduced voltage is preferable to the use of a starting motor. If especially low starting kv-a. are desired, oil pressure starting equipment should be provided.

6. The least disturbance on synchronizing will take place when the field current at changeover from the tap to full voltage is made equal to $(T + 1)$ times the no-load field current, or roughly, 40 per cent of the rated field current of a standard condenser.

7. By the use of a saturated magnetic circuit or a quick response excitation system, the already great voltage stabilizing influence of a synchronous condenser can be considerably increased.

8. Present standard condensers have adequate synchronizing power, and should stay in step on system disturbances in which the frequency does not change faster than 5 per cent per sec. at rated excitation, or one-half per cent per sec. at zero excitation.

9. The use of asynchronous condensers presents no important advantages over the usual synchronous condensers, and is accompanied by a sacrifice in cost and losses.

The author wishes to express his appreciation of the assistance given him by Messrs. L. W. Riggs and O. A. Gustafson in the preparation of this paper.

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Discussion

R. H. Park: Usually, synchronous condensers are purchased for power factor correction and voltage regulation. It is sometimes desirable, however, to purchase additional condenser capacity in order to secure greater stability either in steady operation, or during transient periods of instability, such as are occasioned by short circuits and sudden load changes.

The ability of a condenser to improve stability under steady conditions depends upon the values of its synchronous and transient reactances, although the relative importance of these two has not yet been convincingly established. It also depends upon the type of voltage regulator employed and on the speed of response of its exciter.

On the other hand, the ability of a condenser to improve stability during system transients occasioned by short circuits

is determined largely by the amount of leading current which the condenser can supply to the system, and thus by the transient reactance and the speed with which the excitation system can vary the condenser field voltage over a wide range. If insufficient range of exciter voltage is available, the advantage derived by effecting the available voltage change quickly will be slight.

Thus, where stability considerations are important, it may be desirable to provide an exciter of considerably greater voltage range than for normal application. Also, it may be desirable to use special condensers designed for low transient reactance. I should like to ask Mr. Alger, therefore, which is economically more desirable, to secure low transient reactance by a special design of condenser, or by using a standard condenser of larger size.

M. W. Smith: Mr. Alger has brought out some interesting and practical considerations in the design and operation of synchronous condensers. A timely plea has also been made for standardization of requirements and characteristics which affect design proportions. Standardization is, of course, desirable in all classes of apparatus, but for obvious reasons, synchronous condensers probably offer more possibilities in this respect than any other large rotating apparatus. Considerable movement in this direction can be made without impairing the quality of the apparatus, and which will result in benefits to both the operating companies and the manufacturers.

Past experience has usually shown that the variable having most effect on synchronous-condenser design proportions, is the ratio of lagging to leading kv-a. capacity. Mr. Alger has proposed several methods for obtaining increased lagging kv-a. capacity from machines of standard proportions. All of these methods may be applied in special cases, but the use of suitable reactors is about the only method proposed that can be offered as a general application. It seems doubtful if even this method can be applied economically in most cases. It has been noted that where large percentages of lagging kv-a. capacity are specified, machines of special and abnormal proportions have usually been supplied after all conditions were considered. This results in units which are comparatively expensive and inefficient. Every effort should, therefore, be made to keep the requirement for lagging capacity down as close to 50 per cent of the leading kv-a. capacity as possible. This consideration should be kept in mind in the operation and layout of power system as far as economic considerations will permit.

P. L. Alger: Answering Mr. Park's inquiry, I believe that the most economical way to secure abnormally low transient reactance in a synchronous condenser is to use an oversized machine with a standard field, but a special armature. The per cent reactance is nearly the same for all standard machines, so that by merely using the next larger standard rating, a proportional decrease in reactance is secured. However, this larger machine will have more armature copper and larger slots, than are necessary for the new rating, and so a further reduction in the per cent transient reactance can be secured by using a special armature winding with shallower slots. The saving in cost of copper and insulation here will more than offset the cost of the special features. By these means, the transient reactance can be reduced about 10 per cent faster than the corresponding standard rating is increased. By using field poles, shorter and narrower than standard, additional gains could be made, but at greater expense, and with a greater loss of efficiency.

Oscillograph Recording Apparatus
For Transmission Line Studies

BY JOSEPH W. LEGG[1]
Associate, A. I. E. E.

Synopsis.—*Part I is an introduction, showing the need for reliable records of power disturbances in transmission lines, and showing that the incandescent-lamp oscillograph is the only practicable recorder of such chance disturbances.*

Part II describes the Power Osiso which is a very compact and highly efficient oscillograph, having an instantaneous wattmeter, a permanent-magnet galvanometer, and a relay arrangement with control for automatic operation on chance disturbances. The various auxiliary apparatus, such as daylight-loading film holders, 6-volt motor, potential circuit control, etc., is also described, together with different connections for the same.

Part III describes the Multi-Element Oscillograph, which gives from 3 to 9 simultaneous records on one film, also the various auxiliary apparatus and the possible combinations thereof. A detailed description is given of the automatic operation equipment and its action in recording chance disturbances.

PART I. INTRODUCTION

IN this day of complex power circuits it is very desirable to have reliable records of system behavior during disturbances. A most satisfactory recorder of such disturbances is an oscillograph using an incandescent lamp, because such an instrument can be easily arranged to function automatically and to give sufficiently high-speed records.

Automatic operation of standard oscillographs on chance disturbances[2] has been advocated for nearly a decade, but has not been utilized by operating engineers until recently. The present stage of development of such apparatus has advanced to such an extent that it is even possible to obtain records within the first half cycle of power flow following a lightning stroke or other chance disturbances. Thus this apparatus is much quicker in action than is absolutely necessary for stability studies and will even show the rupturing characteristics of lightning arresters and high-speed circuit breakers.

It was hoped that graphic-chart instruments could be made fast enough to catch the surges in power which affect the stability of a system. However when charts were compared with oscillograms, taken simultaneously, it was seen that the highest-speed graphic instruments are hopelessly slow in following rapid fluctuations in power. An instantaneous oscillographic wattmeter was calculated some time ago, but its complete development was delayed because of the hope that a practicable graphic instrument could be made fast enough for stability investigations. When it was found that a reconstructed high-speed graphic instrument, with over fifty times normal input, would not tell as complete a story as the oscillographic wattmeter, then it was conceded that the oscillograph is the only practicable instrument for recording power disturbances. Furthermore, the reconstructed high-speed graphic required an elaborate installation of extra potential and current transformers, besides multi-contact relays to cut out the instrument before it could be destroyed by fifty-times normal input. On the other hand, the oscillographic wattmeter takes less energy than standard graphic instruments.

This paper is to describe improved forms of oscillographs applicable to power circuit analysis, and to indicate the types of elements new or old, required for recording the electrical quantities involved, and their proper arrangement in the various circuits. The outfits discussed are in two different forms. The smaller outfit is known as the Power Osiso and gives one or two simultaneous records, of instantaneous power or potential or current, on one film 3⅝ in. wide. The larger outfit is known as the Multi-Element Oscillograph, see Fig. 1, and gives from three to nine simultaneous records on one film 7 in. wide. Each outfit may be equipped with instantaneous wattmeter elements and with a suitable relay arrangement for automatic operation on chance disturbances.

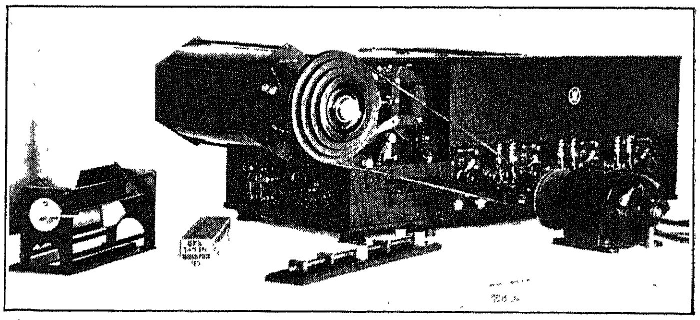

FIG. 1—COMPLETE MULTI-ELEMENT OSCILLOGRAPH WITH DRIVING-MOTOR ATTACHED TO FILM HOLDER, VIEWING MIRRORS RESTING AT ONE SIDE

PART II. THE POWER OSISO

There are several forms of the Osiso,[3] but only the newest form, developed especially for power investigations, will be described in detail in this paper. Each Osiso is a very portable and highly efficient oscillograph

1. Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
2. See TRANS. A. I. E. E. Vol. XLII, 1923, p. 385 section on Automatic Operation, in article entitled *Expansion of Oscillography by the Portable Instrument*, by the author.

Presented at the Pacific Coast Convention of the A. I. E. E., Del Monte, Calif., Sept. 13-16, 1927.

3. See *The Electric Journal* for December 1924 and July 1927.

which gives more clean cut photographic records with a two-watt lamp than we have been able to obtain with any other oscillograph even though the latter uses a direct-current arc lamp. The Osiso is 6¼ in. wide, 9 in. high, and 10 in. long, including all parts except the photographic film holder and its driving motor. Fig. 2 shows the original form of the Osiso with a daylight-loading film holder and a six-volt shunt motor attached. The micarta case contains the incandescent

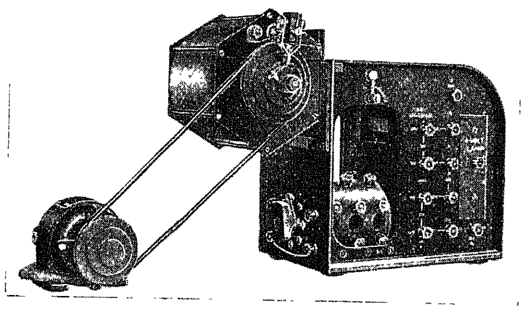

Fig. 2—Standard OSISO with Daylight-Loading Film Holder and Driving Motor Attached

lamp illuminant; resistors for the potential circuits, up to 250 volts; one or two galvanometer elements; complete optical system; and convenient binding posts for all connections. There are side openings which can be fitted with detachable panels equipped according to the particular application desired.

The Power Osiso is a special development in this line for power-circuit investigations. Fig. 3 shows a cross sectional view of the Power Osiso equipped with one instantaneous wattmeter and one permanent-magnet galvanometer, for recording either potential or current waves. The Osiso lamp was especially developed for this extremely portable oscillograph. The lamp has an incandescent filament, a special bulb, and a double-contact vase for candelabra bayonet sockets. The filament is kept straight by a spring support. Two capacities are furnished, one for approximately one-half ampere, and the other for approximately two amperes, both at 4 volts.

The one-half ampere lamp has the characteristic of lighting quickly when connected across a constant potential supply with no series resistance, and going out quickly when disconnected from the supply. This makes it possible to take a single photographic exposure, on a fast rotating film, by exciting the lamp for one revolution of the film drum. This lamp gives sufficient light, on short-time abnormal voltages, to take fairly high-speed oscillograms (10 in. in 0.05 second).

The two-ampere lamp gives splendid illumination for viewing audio-frequency waves, so that several people may see the waves at the same time. Moderate-speed oscillograms may be taken for quite a period of time, with normal, or slightly abnormal, voltage on this lamp.

Undesirable reflections from the rear, inside, surface of the globe have been prevented by a special construction of the glass bulb.

The vertical filament of the lamp shines on the tiny mirrors of the two vertical vibrators of standard design. Beams of light are reflected from there to two reflecting prisms which in turn reflect each beam of light upwards to a long horizontal reflecting prism and from thence, horizontally, to the front of the instrument. Here the narrow ribbon-like beams pass through the cylindrical lens and are condensed to two separate points on the photographic film. In the permanent magnet galvanometer the vibrator mirror deflects in proportion to the instantaneous value of current passing through the vibrator strips.

Instantaneous Wattmeter

The vibrator element of the instantaneous wattmeter is the same as that which has been used with electro-magnet and permanent-magnet galvanometers for many years. As is usual with oscillographs the vibrators are surrounded by a transparent oil for critically damping the movements. The electro-magnet is very much smaller and lighter in weight than that of any other oscillograph. The complete galvanometers are but 3¼ in. high, overall, above the base of the Osiso. The laminated hypernick steel core of the wattmeter magnet and its copper winding respond to instantaneous values of alternating currents. Fig. 4

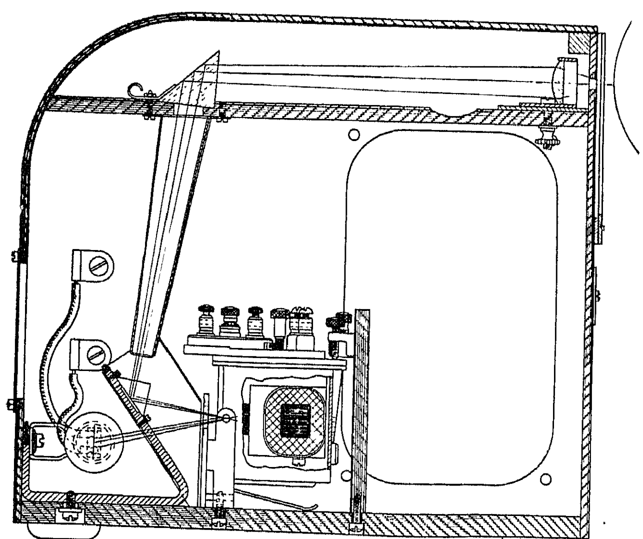

Fig. 3—Cross Sectional View of the Power OSISO

shows the instantaneous watt-galvanometer disassembled. Normal magnetic strength is obtained with a drop of only 1½ volt at 5 amperes, with 60 cycles current. With this magnet excitation the vibrator consumes but 0.03 amperes, r. m. s., from the potential circuit to give one inch extreme deflection on the photographic film. The total energy consumption is less than one per cent of that taken by the reconstructed high-speed graphic instruments whose response was more than 100 times slower.

Even though the Osiso is a small fraction of the size and weight of an arc-lamp oscillograph, it is just as sensitive and considerably more efficient. Furthermore the Osiso will do many things which cannot be done with any predecessor. When in a single-phase system this instrument shows true instantaneous power. The instantaneous watt record enables one to scale off values of kv-a., power-factor, and average power. Fig. 5 shows how these values may be taken from the curve, assuming that the records are sine waves. The single-phase watt galvanometer may be connected in three-phase lines by means of a three-circuit resistor or twin-transformer arrangement, either of which may be supplied within the Osiso proper. In most power-system disturbances, the ground current becomes zero, or negligible, by the time the surges of actual power are important. Those cases in which the disturbances are most severe, the system approaching instability, the power continues to oscillate some time after the relief of short circuit. Hence the single-phase wattmeter, properly connected, shows the important power surges, and also shows the variations in kv-a. and power factor. A polyphase instantaneous watt-

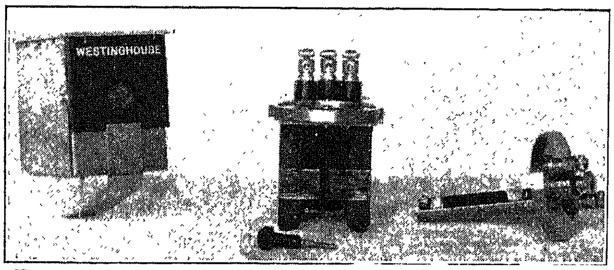

FIG. 4—THE INSTANTANEOUS WATT GALVANOMETER DISASSEMBLED

meter (described later) has been designed to go in the same space as the single-phase or the permanent-magnet units. However, the less expensive and more accurate single-phase unit tells a greater story than the polyphase unit, since the latter will not show kv-a. and power factor.

All these vibrator elements give a deflection proportional to the current, potential, or power which they are recording. The deflections are not proportional to the square of the current, as is the case in a-c. indicators, but to the first power of the current as in a D'Arsonval instrument. The galvanometers are true oscillograph galvanometers and not compromises or improvised indicators. In the few cases where it is desired to give a deflection in proportion to the heating effect of the current, this may be done by placing the single-phase wattmeter vibrator across a 5-ampere shunt which is in series with the 5-ampere current coil of the wattmeter.

GALVANOMETER CONNECTIONS

This paper does not attempt to show all the various ways in which the oscillograph galvanometers may be connected in the instrument transformer circuits of transmission lines. Reference may be made to the contemporary paper by Messrs. J. C. Wood, Lloyd F. Hunt, and S. C. Griscom entitled *Transients due to Short Circuits* and to Mr. Roy Wilkin's paper on *Practical Aspects of System Stability*, A. I. E. E. TRANSACTIONS of 1926, and to an article by R. D. Evans entitled "New Sequence System of Polyphase Meters" in the *Electrical World*, February 10, 1923.

In stability analyses one is interested in power measurement largely because of its effect upon acceleration or deceleration of the rotors of generators. The

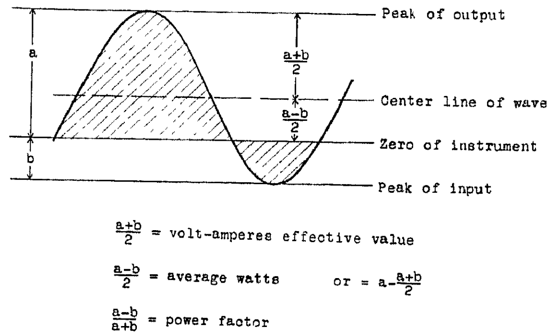

FIG. 5—INSTANTANEOUS WATT DIAGRAM

low sides of transformers to which generators are connected are usually in delta, so that in this circuit there can only be positive and negative sequence power. The negative sequence power is usually small or can be corrected for, or calculated, so that the important quantity is positive sequence power. This can be obtained readily by the sequence connections.

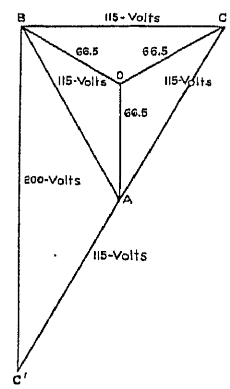

FIG. 6—DIAGRAM OF ARTIFICIAL NEUTRAL, AND POTENTIAL TRANSFORMER VOLTAGES

Various forms of phase-sequence networks may be used for certain tests, but for most purposes where only two simultaneous records are to be taken it will be found best to use the single-phase instantaneous watt-meter connected to show three-phase power, kilovolt-amperes, and power factor. The permanent-magnet galvanometer may then be used to record any one line current, or any line potential from the neutral to any line. Standard potential and current transformers, used for other instruments, will supply the necessary power for the oscillograph galvanometers without affecting the reading of the other instruments.

Three-Circuit Resistors

The three-circuit resistor consists of six units of 1000 ohms each, making two units per set. When these sets are Y connected to form an artificial neutral to a three-phase 115 volt circuit (Fig. 6) the instantaneous wattmeter vibrator is placed in series with any one of these sets and the current coil is placed in the 5-ampere secondary of the current transformer pertaining to the line of that set. This arrangement gives ample variation in deflection for all currents from 1.5 amperes to

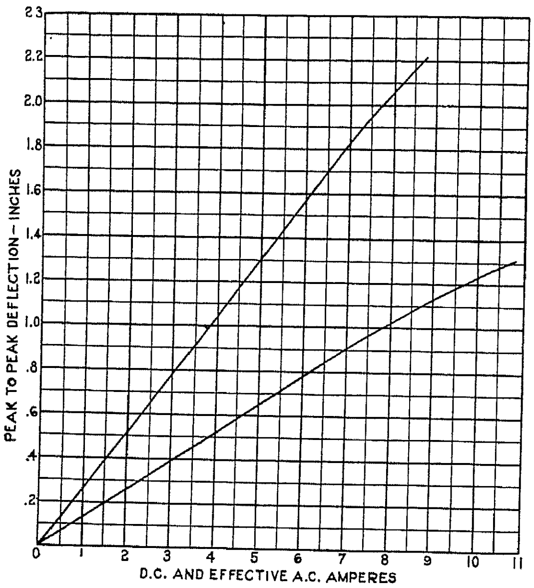

Fig. 7—Typical Calibration Curve of Instantaneous Wattmeter, with 0.033 Ampere in Vibrator

approximately 8 amperes, where saturation of the iron begins to be appreciable. See Fig. 7, taken with 0.033 ampere in vibrator circuit. A tap is provided on the current coil so that 30 amperes gives the same flux density as 5 amperes through the whole coil. Thus by using the whole coil for currents up to 8 amperes, and the tapped section for overload currents from 6 to 40 amperes, this arrangement covers a broader range than is usually required for studying staged or chance disturbances in a-c. power systems.

Twin-Transformer Panel

A panel is available carrying two small potential transformers and two rheostats so arranged as to fit in the side openings of the Power Osiso. The transformers are wound for 120 to 1.2 volts, and furnish a convenient means of replacing resistances in making the necessary phase-changing connections in the application of the single-phase wattmeter to the three-phase circuit. In the use of the polyphase-wattmeter element described below, the transformers are necessary because of the interconnection of the different phase circuits in the wattmeter.

Polyphase Wattmeter

The vibrating part of the polyphase wattmeter is exactly the same as that of the ordinary sensitive vibrator except that the two vibrator strips are connected together at their center, under the tiny mirror, by a short length of the same material. This construction is just as strong as for the single-phase vibrator and permits the vibrator strips to be under the usual tension of approximately 50,000 lb. per sq. in. The ivory bridges, on the vibrator frame of this polyphase unit, are the same distance apart (one inch) as in the single-phase unit. The two upper extremities of the vibrator strips are connected to the usual binding posts. In this case there are two lower extremities (instead of the usual loop) and these are connected to levers and thence to insulated leads which pass to two other binding posts on the element top. The levers are insulated from the frame, and from each other, and are connected, by an equalizer, to the usual tension spring.

In this polyphase galvanometer there are two separate field windings, on separate, inclined, laminated iron cores. The active air gaps in all magnets are 0.032 in. or less, and it is in this space that the vibrators act without touching the pole faces of the magnets.

This polyphase oscillographic wattmeter will not show kv-a. nor power factor, but is better than the single-phase instrument for showing true power during transients in a delta-connected circuit. It is, of course, not applicable at the instant current flows through the fourth wire (ground) in a star connected circuit.

Automatic Operation Panel

A full-automatic operation panel is designed to occupy the opening in either side of the Osiso. This panel is shown in Fig. 8, with internal and external wiring in Fig. 9. The panel has an initiating relay,

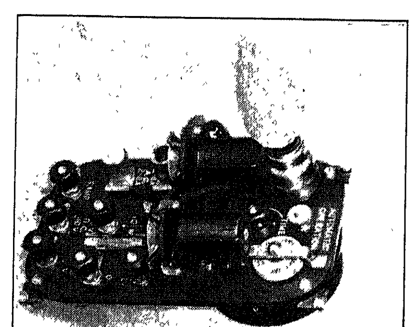

Fig. 8—Automatic Operation Panel for the OSISO

to operate from the secondary of a current transformer, preferably in the ground-to-neutral circuit of the power system. The closing of this relay starts the Osiso to function on a chance disturbance. A second relay acts to hold the lamp and motor circuit closed. A thermostatic cut-out may be set to drop out the second relay after the desired period of time has elapsed, usually between 3 and 15 sec. A rheostat or potentiometer is supplied on the panel to control the time of heating the thermostatic cutout. A socket is included

for a protective lamp which also acts as a signal. This automatic-operation panel may be connected in several different ways according to the type of automatic operation desired. One connection is for single, quick-automatic operation. This throws the 4-volt, ½ ampere Osiso lamp across a 20-microfarad condenser, charged to 110 volts direct current, when the initiating relay closes. This is shown in the upper right-hand diagram of Fig. 9. The photographic film must be kept rotating continuously for such high-speed operation. The thermostatic cutout is set to open the second relay by the time the film drum has made one revolution. A fuse blows when both relays are closed so that the apparatus will not operate again until the film is changed by the station attendant.

start of a short circuit on a direct-current power system.

Repeated Action

Repeated automatic operation may be obtained by connecting the panel according to the lower right-hand diagram in Fig. 9. In this case the records do not start as quickly, since the film must be brought up to speed by the driving motor and the lamp is merely thrown across six volts of the storage battery. In this case the film travels forward a few inches each operation and requires no attention until many automatic operations have taken place, each recording a different disturbance. If it is desired, a 10-in. or a 5-ft. film may be driven entirely through on the first operation, but usually several records will be taken on

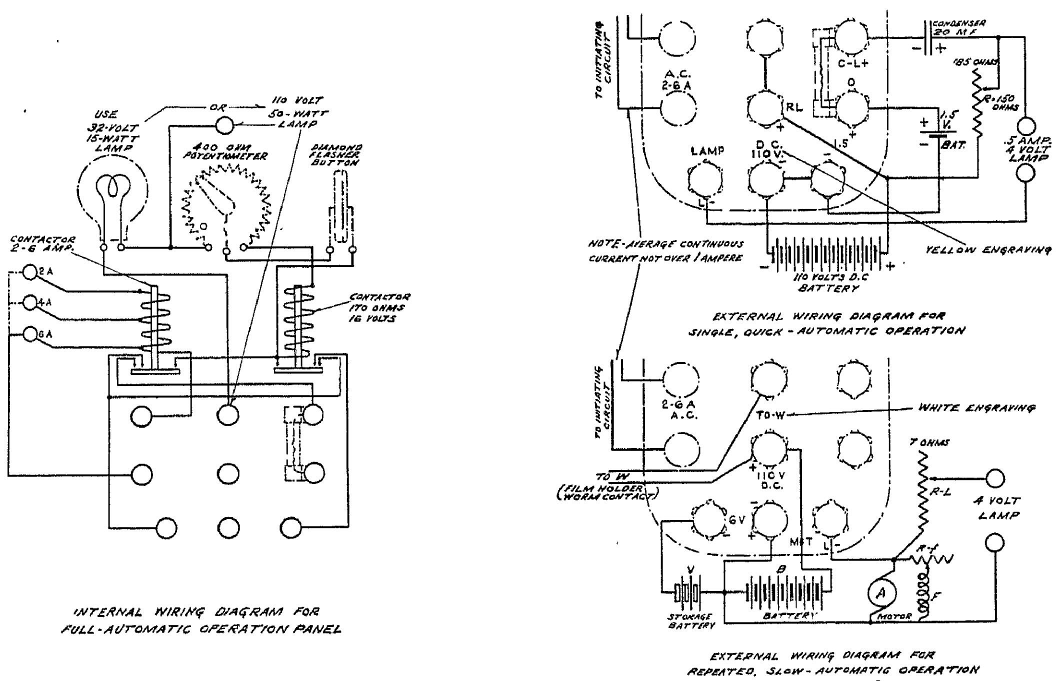

Fig. 9—Internal and External Wiring Diagram for Automatic Operation

Quick Action

Since the lamp comes up to full brilliancy in less than a thousandth of a second after the closing of the first relay, and since this relay will operate in a fraction of a cycle under a great sudden overload, and since the film is rotating continuously, a perfect oscillographic record is started several cycles before the oil circuit breaker can function. If the chance disturbances clear themselves before the first or succeeding operation of the breaker the record will show this fact. If a power surge follows the circuit breaker action, the record shows that also. For such operation the film holder must be supplied with a strip film which must pass entirely around the drum, so that all of the record will be there irrespective of the position of the drum at the instant of the lighting of the lamp. With a high-speed direct-current relay, operating on the steepness of wave front principle, it is possible to start exposures within two thousandths of a second after the

each 5-ft. film. In any case the photographic film can be brought up to sufficient speed to give a good record of the action of large oil circuit breakers. The film speed will be fairly uniform during the power surges which may follow the breaker action.

Driving Motors

Fig. 10 shows the Power Osiso with the automatic-operation panel and 6-volt shunt-motor unit. The driving motor unit is arranged with a field rheostat and a double-pole switch so that the armature may be supplied with 2, 4, or 6 volts to give a considerable range of speed to the photographic film. A 110-volt series-motor unit is available with a rheostat across the armature brushes. This is satisfactory for continuous rotation of the film drum but not for quick pick up of speed on repeated automatic operation. The shunt motor brings the film up to constant speed in a much shorter line.

Ten-Inch Records

If the rotating-drum film holder is used, with 10 or 15 in. of film on the drum, it will be necessary to use the pulley-and-gear-reduction unit, or its equivalent, to keep the film speed less than one-third of a revolution per second. With this reduction unit the 10-in. length of film could be adjusted to pass through in four steps of ten sec. each (or eight steps of five sec. each). A contact on the film holder opens the circuit at the end of the film and prevents further operation of the apparatus, until the film is changed.

Daylight-Loading Film Holders

The daylight-loading features of the film holders which are used on the Osiso have been used on the three-element portable oscillographs for some time,[4] and have proved to be very convenient and reliable.

The daylight-loading long-film attachment is shown in place in Fig. 11. This film holder uses standard roll film, 5 ft. long, intended for a 3¼ by 5½ in. camera, or special 10-ft. films wound without the paper ordinarily used to back the film. This film holder passes the film half-way about the main drum and wraps it on the receiving spool. Furthermore, it does this with such

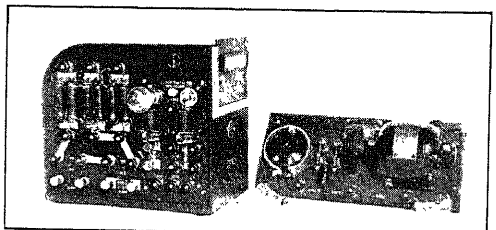

Fig. 10—The Power Osiso with Its Automatic Operation Panel and Six-Volt Motor Unit with Double-Pole Switch and Field Rheostat

uniform velocity that there is no bunching of waves even when there are as many as 100 cycles per inch length of film. For film speeds below 4 in. per sec., it is usually necessary to use the pulley-and-gear-reduction unit. At this speed the Osiso shows each cycle, more clearly than most oscillographs operating at from 2 to 5 times that speed. At this same speed, five records of six sec each could be obtained on one 10-ft. film. With the pulley-and-gear-reduction unit the total time could be increased to five minutes for 10 ft. of film, or 30 automatic operations of 10 sec. each, thus allowing 4 in. per record.

The daylight-loading rotating-drum film holder takes 5 oscillograms, each 10 in. long, on one 10-exposure roll film. An observation window (to show the number printed on the opaque paper of the film) and a winding key make it possible to shift the film after each record is completed. The film may be removed without the use of a dark room, and sent to any photographer for development.

4. *Expansion of Oscillography by the Portable Instrument*, J. W. Legg, Trans., A I. E. E., Vol. XLII, 1923, p. 381.

Full-Circumference Films for Continuous Operation

A dark-room loading film holder is available taking special cut films (from Eastman No. 116 rolls) 15¼ in. long. This full-circumference film is essential for high-speed automatic operation, where the film runs from 5 to 20 rev. per min., continuously, day and night, until the chance disturbance closes the relay for an exposure under the instantaneously obtained desired brilliancy.

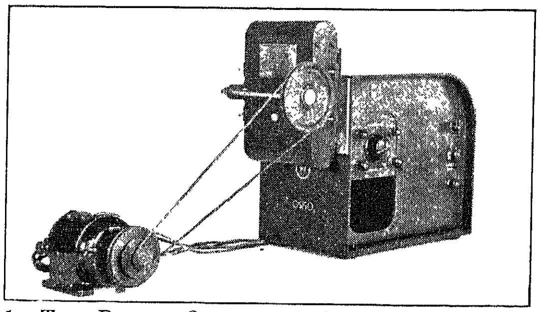

Fig. 11—The Power Osiso with Daylight-Loading Long Film Attachment and Driving Motor

The daylight-loading holder will also take a 15¼ in. film (cut from Eastman No. 130 roll) for high-speed operation on chance disturbances. A speed-reduction attachment, with a 5/6 revolution contact, may be supplied with any rotating-drum film holder. A small pinion and annular-gear give a speed reduction of 24 to 1, while the 3-in. pulley may be driven from the ¾ in. pulley of the motor and thus give a total reduction of 96 to 1. This permits adjustment of the film speed to 1 in. per sec., or 5 in. per sec. This is quite necessary for continuous operation.

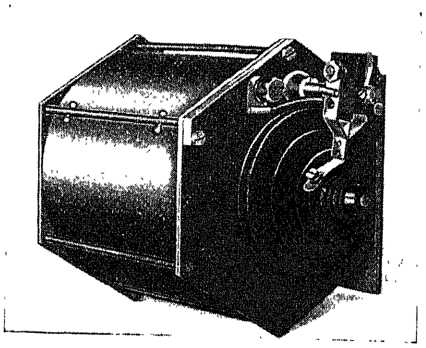

Fig. 12—Daylight-Loading Rotating-Drum Film Holder with Pulley and Worm Contact

Worm Contact

All rotating-drum film holders may be equipped with a one-revolution contact, see Fig. 12. When taking a staged oscillogram this contact is connected in series with the Osiso lamp so as to give one revolution of light exposure on the drum, thus giving but one length of exposure on the film, at 600 rev. per min. or less. For delayed automatic operation, the film-holder contact is

placed in series with the d-c. supply so as to prevent re-exposure of the film after one revolution. This outfit also gives excellent high-speed records of wave forms, telephone currents, inductive interference, vibrations in machines, etc.

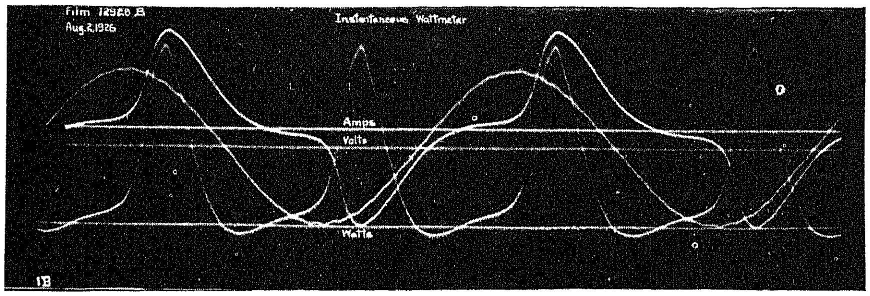

FIG. 13—OSCILLOGRAM OF INSTANTANEOUS WATTS, VOLTS, AND AMPERES. VERY DISTORTED CONDITION

SYNCHRONOUSLY DRIVEN FILMS

The light-weight drum of the dark-room loading film holder may be driven by a synchronous motor at 1200 rev. per min., or at 900 rev. per min., so as to obtain several 60-cycle waves on the one-film all in their proper time-phase relation. Fig. 13 shows an oscillogram of instantaneous watts, instantaneous volts, and distorted instantaneous amperes; on a 60-cycle line. As many as six waves may be taken on the one synchronously driven film by placing the one or two vibrators in the different circuits while the motor keeps the film in synchronism.

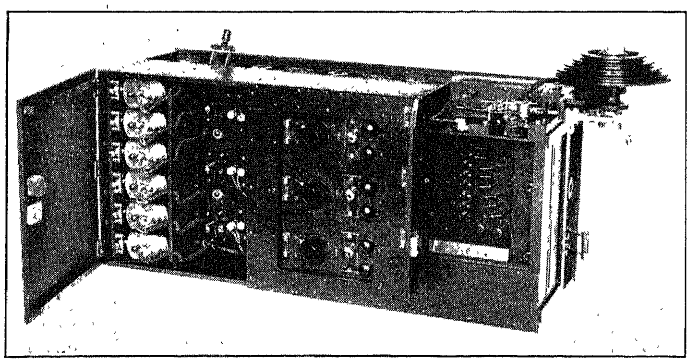

FIG. 14—MAIN UNIT OF MULTI-ELEMENT OSCILLOGRAPH. THIS IS BUT 25 x 11 x 9.5 INCHES OVER-ALL

PART III. THE MULTI-ELEMENT OSCILLOGRAPH

The design of the three-element portable oscillograph described in the 1923 TRANSACTIONS, page 381, and the six-element instrument (mentioned in the September 1926 JOURNAL, p. 881) have been combined and extended to cover instruments with 3, 6, or 9 individual galvanometers, giving up to nine simultaneous records on the 7-in. wide film. The main unit (Fig. 14) of this multi-element oscillograph is but 25 in. long, 11 in. broad, and 9.5 in. high, over all, including everything but the film holder and its driving motor. In the 9-element outfit this case includes: a compact 6-element galvanometer with vertical vibrators; a compact 3-element galvanometer with horizontal vibrators and with reflecting prisms above each; complete optical system, incandescent lamp, and control switch; photographic shutter and remote-control mechanism; eleven dial control resistors; six knife switches; three toggle switches; and binding posts to connect into the various units of the 20,350 ohms of non-inductive resistance in the vibrator circuits.

The film holder and 6-volt shunt motor are all that is essential outside of the main case. A viewing attachment and three 2 to 20 ampere non-inductive shunts are also desirable. This whole oscillograph outfit, including the 6-volt motor, weighs from 90 to 120 lb., according to the number of galvanometer elements, resistors, film holders, etc., included. For many tests on transmission lines, this outfit replaces from two to four 3-element oscillographs, and in addition, gives records which are easier to analyze, since the records are all in the same time-phase relation. This outfit will operate from one large-size 6-volt storage battery.

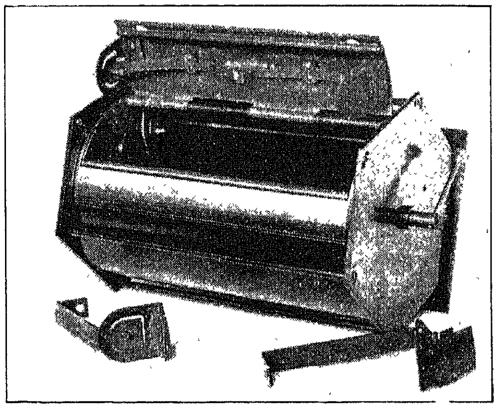

FIG. 15—MULTI-ELEMENT ROTATING DRUM FILM HOLDER SHOWING THE DAYLIGHT-LOADING FEATURES

For this instrument there is provided a rotating-drum film holder similar to that used on the Osiso, only it is wider and will take either 7-in. or 3⅝ in. widths of film (Fig. 15). Each exposure is 10 in. in effective length and may cover a time interval of 0.04 sec. or greater. At this speed, 1200 ft. per min., the film obtains ample illumination from the 3-volt lamp when

the latter is operated, momentarily, on 4 or 5 volts. Standard Eastman No. 115 roll films are used in this daylight-loading film holder. This does away with the necessity for a dark room at the place of tests, and permits any number of exposures to be made with one film holder. Each standard 6-exposure film gives three oscillograms.

If an exposure of more than one second is desired, a pulley-and-gear-reduction unit is necessary. This will give a film exposure range from 2 min. down to 0.04 sec. when operated by the sturdy 6-volt shunt motor supplied with every outfit. This slow-speed drive is very desirable for repeated automatic-operation on chance disturbances.

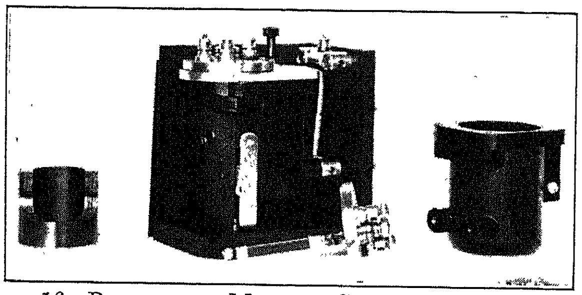

FIG. 16—PERMANENT MAGNET GALVANOMETER SHOWING MAGNET AND WELL AT EACH SIDE, AND VIBRATOR IN FOREGROUND

The long-film holder for this outfit is somewhat similar to that described before, only improvements have been added to make this outfit more reliable at higher speeds. Twenty-four-foot films, 6.5 in. wide, have been run through in as short a time as 4 sec. The maximum speed usually required is but 8 ft. in about five sec. Semi-special films 8 ft. long are available. Standard "Cirkut Outfit" films 3 ft. or 6 ft. long may be used, after slight modifications. This daylight-loading feature is very valuable in taking several successive tests. Half of the film holder remains on the oscillograph while the outer half is removed to reload. An annual gear and pinion reduce the speed of the film drum (12 in. in circumference) to 4 in. per revolution of the driving head instead of the 15 in. of the rotating-drum type. With this arrangement there is seldom need for the addition of the pulley-and-gear-reduction unit, except for very slow repeated automatic operation.

VERTICAL GALVANOMETERS

Six vertical type galvanometers may be included in one frame. This 6-element galvanometer is but 3¼ by 3⅝ by 10⅜ in. over all, and is insulated to stand a test of 5000 volts between adjacent vibrator elements. Each element may be of the permanent magnet type or one or more elements may be of the instantaneous wattmeter type, having laminated-core electro-magnets.

A permanent magnet single-element galvanometer is shown partly disassembled in Fig. 16. A permanent magnet is shown externally at one side and a vibrator element at the other side. The galvanometer well is moulded in one piece, from moldata. The standard vibrator has a natural period of between 5000 and 6000 cycles per sec. undamped. When immersed in oil, within the galvanometer well, the vibrator has no natural period and responds, very satisfactorily, to frequencies up to 4000 cycles, and shows up much higher frequencies with a corresponding reduction in sensitivity. The standard vibrator has a resistance of approximately 1.3 ohms including the protective fuse, and requires approximately 0.12 amperes for one in. deflection of direct current. The sensitive vibrator requires approximately 0.03 ampere per in. deflection, and has a natural period of approximately 3000 cycles per sec., when undamped.

The instantaneous wattmeter, described with the power Osiso, may be used in place of one or more permanent magnet galvanometer units in the 6-element galvanometer frame. The only difference between the multi-element oscillograph and that of the Osiso is the difference in the power of the objective lens, which forms the window in front of the vibrator mirror. For most transmission-line studies, the total number of permanent-magnet and a-c. field galvanometers units may be six, within the one frame. The reaction between an instantaneous wattmeter and an adjacent galvanometer unit is so very small that it is negligible for all cases except where the film is driven very fast, and where it is desired to analyze the power wave for the higher harmonics. Where absolutely no reaction is required, the instantaneous wattmeter should be separated from the next galvanometer by a vacant space. With one instantaneous wattmeter and one vacant space, there could be a total of eight galvanometers in the one oscillograph. With two wattmeters, and two vacant spaces, there could still be a total of

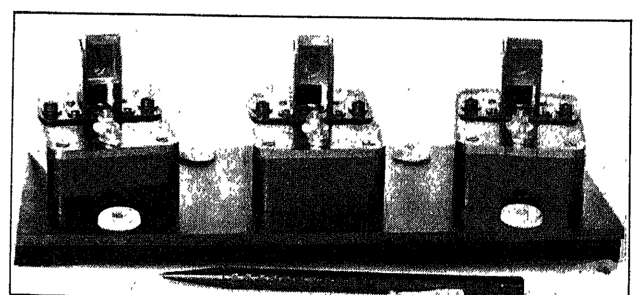

FIG. 17—HORIZONTAL GALVANOMETER, 7TH, 8TH, AND 9TH ELEMENTS

seven galvanometers. When vacant spaces are thus made available each vacant space may be traversed by a light beam, thereby adding a zero line, or timing line or other indicating or reference line on the photographic film. The whole nine beams of light will be found very valuable even when there are but six galvanometers in use.

HORIZONTAL GALVANOMETERS

The 7th, 8th, and 9th galvanometers are assembled on one base and are thus shown in Fig. 17. These

galvanometers have their vibrators in a horizontal plane. Above each vibrator mirror is a reflecting prism which catches the incoming beam of light, from the optical box, throws it down to the vibrator mirror, and then throws it towards the photographic film after it is reflected from the vibrator and after it has twice passed through the objective lens. Each horizontal galvanometer is but 2 in. wide, $2\frac{3}{4}$ in. long, and $1\frac{3}{4}$ in. high, over-all. The reflecting prism above each

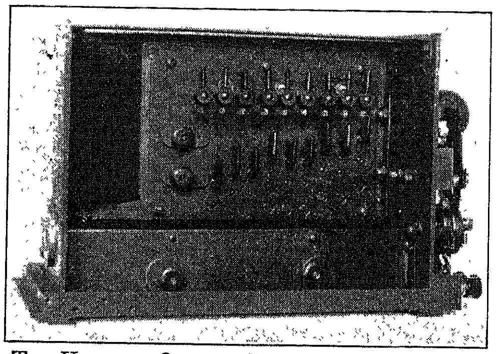

FIG. 18—TOP VIEW OF OPTICAL BOX, SHOWING PRISM AND SLOT ADJUSTMENTS, AND TRIPPING MAGNET AT RIGHT

galvanometer is so narrow that it does not interfere with the other beams of light which pass from the optical box to the six vertical galvanometers and thence forward to the photographic film. Nine galvanometers all in a row would be crowding things too much and would lessen the efficiency of the apparatus. The arrangement is very satisfactory with six vertical and three horizontal galvanometers, all within a cabinet whose outside width is but 11 in.

The horizontal galvanometers are oil tight and have the same sensitivity and frequency response as the other standard vibrators. They are supplied as instantaneous voltmeters or ammeters, but not as instantaneous wattmeters.

THE NINE-BEAM OPTICAL SYSTEM

The whole optical system is complete in one removable box, except for the tiny mirrors and objective lenses in the galvanometers. This unit is shown in Fig. 18. The face of this unit forms the face of the oscillograph proper while the remainder is hidden within the micarta case of the oscillograph. Spherical condensing lenses are located beneath the optical floor (Fig. 19). These are used to concentrate the light from the 3-volt 9-ampere lamp on the vibrator mirrors. Nine reflecting prisms are located beneath the optical floor to direct this light to each individual vibrator mirror. An adjustable slot is located just beyond each reflecting prism to vary the width of the beam of light which passes to the moving film. Many adjustments, which might be accidentally thrown out of line in older instruments, have been made permanent in this apparatus by the proper design of each individual part. The adjustments which remain are very simple and are unaffected by ordinary handling of the instrument. The usual ball-and-socket adjustment of the reflecting prisms has been greatly improved so that there is no harmful sidewise motion. All adjustments are easily accessible by merely raising the front cover of the oscillograph proper. Levers are used as handles in making the adjustments. These point in the direction of the beams of light and so show, at a glance, the condition of adjustment.

The shutter mechanism is very nearly the same as described for the 3-element portable oscillograph, in the July 1920 A. I. E. E. JOURNAL, on page 674 to 679 (of Vol. XXXIX). This shutter is mechanically operated to give one revolution of exposure to the fast rotating film. Being a focal-plane shutter, near the film, it more effectively keeps out all extraneous light from the film and permits the operator to glance at the illumination of the galvanometer without bothering with the shutter. A tripping magnet, remote-control switch, and cutout switch are included in the optical-box unit. The tripping magnet operates as soon as abnormal voltage is applied to the incandescent-lamp illuminant. A contactor, on the film-holder driving-head shaft, is set to operate the tripping magnet at any desired fraction of a revolution, ahead of the start of exposure on the film, equal in time to the time lag of the remote-controlled apparatus being studied. With this arrangement on staged tests, the remote-controlled power apparatus is started to function just in time so that its electrical phenomena will be photographed on the high-speed film, while the oscillograph lamp is at greatly abnormal brilliancy. The closing of the mechanical shutter, at the end of the film, also cuts off the lamp and hence the life of the lamp is conserved.

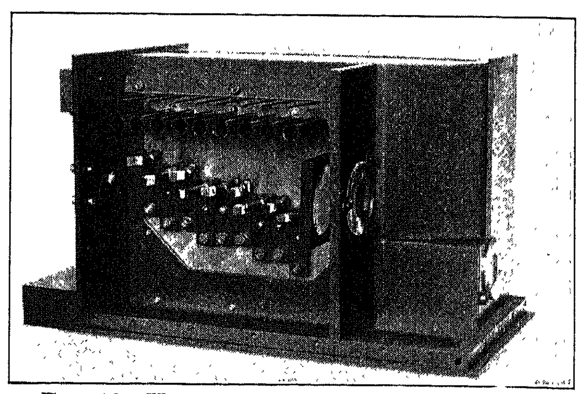

FIG. 19—UNDERSIDE VIEW OF OPTICAL BOX

THE CONTROL UNIT FOR LAMP AND MOTOR

The lamp-control panel (Fig. 20), is located on the front of the oscillograph in a cavity under the optical box. This unit is internally connected to the lamp, cut-out switch, tripping magnet, and contactor. Binding posts are provided to connect in the 6-volt storage battery and the 6-volt shunt motor. The lamp-control switch is set at 3 volts for viewing and calibrating purposes, and at 3.5, 4, or 5 volts for slow-speed

or high-speed oscillograms. A double-pole knife switch is provided with an arrangement so that it may be closed by the operator pulling a cord from a distance. The closing of this switch starts up the motor, lights the lamp, starts the remote control mechanism functioning in the power apparatus, and causes an oscillogram to be taken which will show all the desired details of the operation of the power apparatus. The cut-out switch may be connected to stop the motor as well as to cut off the lamp, at the end of the exposure.

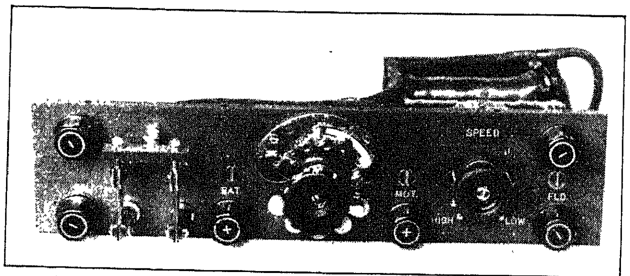

FIG. 20—CONTROL UNIT FOR LAMP AND MOTOR

VIBRATOR RESISTORS

The standard resistor unit to control the 6-element galvanometer is shown in Fig. 21. This consists of four sections of 5000 ohms each and four sections with 50 ohms each. There are eight dial switches, to control these units, and six double-pole knife switches in the vibrator circuits. This whole resistor unit, with a total of 20,200 ohms of non-inductive resistance, fits under the galvanometer compartment in the main case of the oscillograph. This arrangement places sufficient resistance in three of the vibrator circuits to take transient potential peaks up to 1500 volts. One 5000-ohm unit acts as a spare and may be placed in series with any of these three vibrators so as to catch a peak of 3000 volts. This spare may be placed in series with a fourth low-resistance vibrator so as to record four simultaneous voltages. Likewise three of the low-resistance sections are permanently connected in series with three other vibrators. A fourth low-resistance section may be connected in series with any vibrator so as to give control of voltage in small steps.

A fuse is included in each vibrator circuit. This fuse is strung with vibrator ribbon. Since the ribbon of the fuse is in air and the ribbon of the vibrator is in oil, the fuse is a very good protection to the vibrator. A fuse is also made with a spring which keeps the fuse at a greater tension than the vibrator strip. With this arrangement the fuse is a perfect protector of the vibrator.

HORIZONTAL RESISTOR

The resistor unit for the horizontal galvanometers is set in below the surface of the top of the oscillograph as shown in Fig. 14. This unit has three: 50-ohm rheostats, toggle switches, fuses, and sets of binding posts. This arrangement is suitable for controlling the 7th, 8th, and 9th vibrators when used to record current, or potentials below 10 volts. For power-circuit investigation: one of these vibrators may be used to record current from neutral to ground; another one mechanical movement of a circuit breaker, or relative displacement of certain parts; and the last, rev. per min., pressure, relay action, or some other function which may not be a pure electrical quantity.

SIMULTANEOUS VIEWING AND PHOTOGRAPHING

An attachment has been developed[5] whereby the operator may continuously view several waves during the photographic exposure, as well as just previous to it. This is made possible by shifting three of the optical slots, with the levers marked "7," "8," and "9," shown in Fig. 18, so that three of the vertical galvanometers have two light beams apiece, one beam being reflected back to the film holder and the other to a reflecting prism and thence up to the viewing attachment in its new position over the optical box. Since there are but nine beams of light, the sum of the number of waves photographed and the number simultaneously viewed cannot be more than nine. Three of the waves viewed can be simultaneously photographed. When the six-element galvanometer is used without the 7th, 8th, and 9th galvanometers, it is possible both to photograph six waves and to view simultaneously three of them, and the viewing can be done both before and during the exposure. This simultaneous viewing and photographing attachment is very valuable for certain investigations where unusual conditions develop at irregular intervals.

A-C. SUPPLY UNIT

A unit (Fig. 22) has been developed, with a transformer, a back-geared induction motor, proper fuses and switches, and convenient leads to connect this unit to the oscillograph. This outfit is on a base similar to that

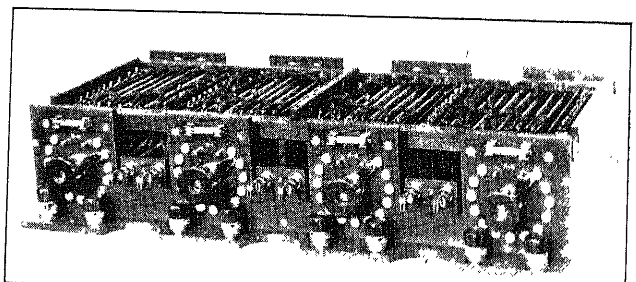

FIG. 21—STANDARD RESISTANCE UNIT TO CONTROL THE SIX ELEMENT GALVANOMETER

of the oscillograph case, but considerably shorter. The unit will operate from 100-120 volts or 200-240 volts supply of 25, 50, or 60 cycle frequency. This is a very desirable auxiliary for laboratory testing. It gives a speed range for the rotating film of from 685 rev. per min. down to 6.1 rev. per min. with 25 cycle supply, or 1010 to 15.1 rev. per min., with 60 cycle

5. See the authosr' discussion of Mr. Curtis' Paper in the A. I. E. E. TRANS., Vol. XLIV, 1925, pp. 271 and 272.

supply. This means from 0.04 sec. to 6.75 sec. per 10-in. length of film. With the long film holder, the lower limit of speed would be 720 sec. (or 12 min.) for 24 ft. of film. This outfit is particularly good for simultaneous viewing and will operate the viewing attachment continuously, and give excellent repetition of film speed when hundreds of oscillograms are to be taken with a constant time component on all films. The heavy-

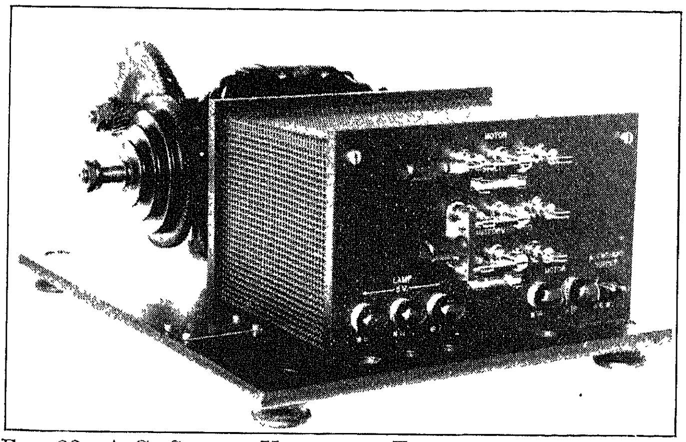

FIG. 22—A-C. SUPPLY UNIT WITH TRANSFORMER AND BACK-GEARED MOTOR

current low-voltage winding of the transformer normally gives 5 to 5.5 volts. This voltage is cut down by the lamp control switch in the oscillograph. This method of resistance control will not be satisfactory for automatic operation on chance disturbances. The 6-volt battery is better for this application.

RELAY FOR AUTOMATIC OPERATION

Single, automatic operation of any one of the incandescent-lamp portable oscillographs is extremely simple. Best results are obtained when the 3-volt lamp is thrown directly across two cells of a large lead-plate storage battery. A standard (type MC) multi-contact relay can be supplied with a special double coil which closes on 3 to 5 amperes a-c. and is held in by 4 to 6 volts d-c. until cut off by the oscillograph. This connects 4 volts directly to the lamp and 6 volts to the motor terminals. The standard cut-out switch on the oscillograph can be connected to drop out the relay and disconnect the battery at the end of the film. One set of contacts, on the relay, short circuits the a-c. pull-in coil after exciting the d-c. hold-in coil. Thus the relay will drop out at the same or lower current than that at which it pulled in. If the a-c. coil was not short circuited, it would not drop out until after the current was reduced to a much lower value than that which closed the relay. If all resistance is cut out of the circuit between the battery and the lamp (heavy leads must be used), then the lamp will attain full photographic brilliancy in less than ⅛ sec. after the closing of the relay contacts. The motor will attain its speed soon after, and a perfect record will be taken of the power surge which follows a chance disturbance in the power system, provided an abnormal current flowed through the relay coil located in the secondary of a standard current transformer.

TERMINAL PANELS

When the oscillograph is to be used solely for a-c. power applications, and especially when the apparatus is to be kept on the line continuously, the 20,000-ohm non-inductive adjustable resistance may be omitted, and either fixed resistors, or oscillograph potential transformers, supplied in its place. Standard terminal panels can be used on the oscillograph when the large resistor unit is omitted. Oscillograph potential transformers (120 volts to 1.2 volts) can be mounted on these panels together with low resistance units, fuses, switches, protections, etc., according to the individual requirements for any particular service.

FULL AUTOMATIC OPERATION UNIT

A full-automatic operation panel has been developed for the multi-element oscillograph. This is much more complete, and more costly in construction, than that used with the Power Osiso. This outfit replaces the standard control unit for lamp and motor, and operates automatically on chance disturbances in power lines. Fig. 23 shows the complete, internal, wiring diagram. The front of the panel looks much like the standard panel which is replaced. However, the lamp-control switch is replaced by a 6-circuit relay, the switch stop is replaced by a thermostatic relay, and the double-pole switch by a duration-control

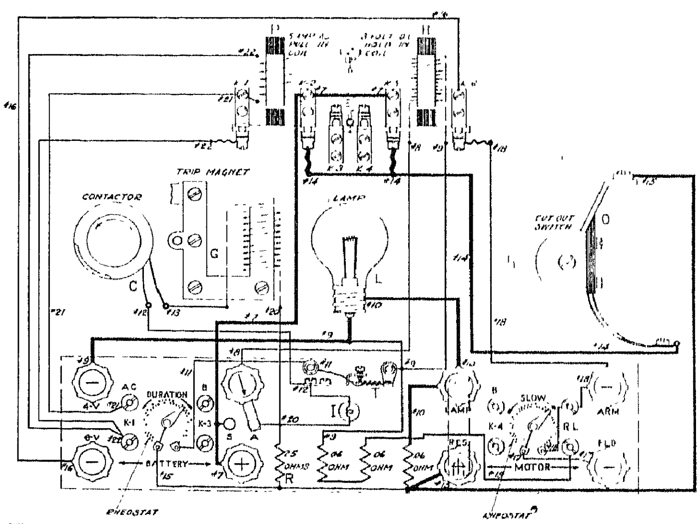

FIG. 23—DIAGRAMMATIC SKETCH OF THE FULL-AUTOMATIC OPERATION UNIT

rheostat. The double-coil relay has four sets of making contacts and two sets of breaking contacts. One making contact, K-1, short circuits the 5-ampere a-c. pull-in coil (P). Two other making contacts (K-2 and K-5) are used in parallel to connect the lamp (L) across the 4 volts of the large storage battery. The remaining making contact is used to connect the motor to 6 volts from the battery. The two break contacts (K-3 and K-4) may be used to short circuit the current

coils of two instantaneous wattmeter galvanometers, if so desired.

The duration-rheostat controls the amount of heat that will be supplied to the bimetallic strip of the thermostatic relay (T). This thermostatic relay, together with the standard oscillograph contactor (C), controls the duration of each automatic operation. The cut-out switch (O) cuts off the lamp and the d-c. holding coil (H), at the end of film. The motor rheostat controls the shunt field current so as to obtain the proper speed of the film.

This apparatus may be used for three types of operation: First, for a *staged test*, such as deliberately throwing a short circuit on the power system to record what happens immediately before, during, and after the application of the short circuit. Second, for one or more automatic operations to be recorded on the ten-in. length of film on the rotating-drum holder. Third, for one or more (usually many) automatic operations to be recorded with the long film attachment so that each record may be of a definite length, both as regards time and distance traveled by the film. For *staged test*: The selector switch is thrown to S, the relay closes on d-c., the motor starts, the lamp lights, a few seconds later the remote-controlled apparatus is set into action, the proper time later the shutter opens and the exposure starts on the film, so as to give a few cycles record of open-circuit voltage followed by short-circuit conditions and the surge of power which follows. At the end of the film the shutter snaps closed and cuts off the lamp and drops out the relay. The controllable delay in the closing of T gives the operator time to leave the apparatus, if located near a dangerous short circuit.

For *automatic operation* with the rotating drum film holder, the selector switch is set at A. The determining over-load current (in secondary of a standard current transformer) closes the relay which is then held in by the battery current. The lamp lights and the motor comes up to speed immediately. A record of short-circuit current is made before the circuit breaker can start to clear the line, the recording continues during the action of the breakers and during the power surge which may follow. When the predetermined period of time has elapsed the thermostatic device causes the relay to drop out and thus cut off the lamp and motor. All is then ready for another chance overload. At the end of the film the shutter closes and knocks open the cut-out switch so no further operation will follow until the film is changed and the shutter reset.

Ideal Repeated Automatic Operation

Repeated automatic operation with the long-film attachment can be made very definite as to time duration and exposed length of film by the action of the contactor C in series with the thermostatic contact of T. Every revolution of C represents ⅓ revolution of the main drum of the long-film holder, or 4 in. of film. By proper setting of the duration rheostat the thermostatic element can be made to operate before the driving head has made one revolution, so as to make each record 4 in. long. Likewise this may be set for two or for three revolutions, so as to give exactly 8 or 12 in. of record for each disturbance. This represents 24, 12, or 8 successive operations on chance disturbances for an 8-ft. film, or a maximum of 76 exposures on a 24-ft. film. Each exposure lasts from 2 to 15 sec., depending on the adjustments made. In most cases of automatic operation it will be necessary to use the gear-reduction unit between the 6-volt motor and the film driving head, in order to obtain a reasonably slow speed for the film, and corresponding low operating cost. However there is no need for this gear-reduction unit when it is desired to drive the film 8 in. per sec., or faster. This speed could be used to drive through a 3-ft. film in less than 5 sec.

A resistance between the binding posts marked "LAMP" and "RES" is normally short-circuited by a link. This link is to be removed whenever the lamp is to be kept lighted for any length of time, such as during visualization with the viewing attachment.

Great care should be used to eliminate all series resistance in the lamp circuit when it is desired to have the lamp come up to full brilliancy as soon as possible, as on automatic operation.

Apparatus Required for Satisfactory Tests on Power Lines

The requirements of oscillograph apparatus may vary considerably according to the data required. The chief necessary parts might be summarized as follows:

A. At least three permanent magnet galvanometer elements and at least one instantaneous wattmeter element to show average watts, kv-a., and power factor. A total of nine elements may be included in one standard outfit.

B. A 20,000-ohm resistor unit with dial switches is very convenient for general testing with six elements. For power tests it may be possible to use 120 to 1.2 volt potential transformers to replace the high resistors. The three additional elements seldom require more than 50 ohms adjustment apiece, such as is supplied in the top panel described.

C. No special relays are required for general testing and for staged tests. The lamp-control panel of the standard oscillograph is well suited to all such tests. When the oscillograph is to be used mainly for automatic operation on chance disturbances it is very convenient to have the full-automatic panel designed for this purpose. However, relays may be used external to the standard outfit and give fairly satisfactory results.

D. A daylight-loading high-speed rotating-drum film holder is very desirable for general testing, but

may be replaced by a daylight-loading long-film holder for repeated automatic operation on chance disturbances. The latter will take films up to 24 ft. in length.

E. A shutter mechanism, remote-control and lamp-extinguishing switches are very valuable for staged tests, but are not needed when the outfit is to be used solely for automatic operation with the long film holder.

F. For purely laboratory testing, it is convenient to use an a-c. supply unit with transformer and back-geared induction motor for driving the film at any desired speed.

G. A sturdy 6-volt shunt motor has proved to be so valuable that it is included in every outfit. This motor is ideal for automatic operation on chance overloads in power systems.

H. Anyone who obtains a 3-element oscillograph will appreciate the fact that it may be made into a 6- or 9-element outfit whenever needed.

I. Mere compactness of apparatus amounts to little compared with the increased reliability and ease of operation which is insured by proper design and construction of these instruments.

Many oscillographs of this general type have been used throughout this country, Japan, and Europe.

Discussion

R. D. Evans: There is one point I should like to emphasize in connection with the instruments described, that is the use of the *power* or *watt element*. We are so accustomed to oscillographic records of voltage and current that a power element record seems a little strange. Power records are, however, so useful for determining what has happened on power systems, that I am sure the use of the power element will find wide application.

High-Voltage Oil Circuit Breakers for Transmission Networks

BY ROY WILKINS[1] and E. A. CRELLIN[1]

Member, A. I. E. E. Member, A. I. E. E.

THE standards of the American Institute of Electrical Engineers define an oil circuit breaker as a "device (other than a fuse) constructed primarily for the interruption, in oil, of a circuit under infrequent abnormal conditions." Common usage, however, has sanctioned the use of the term "circuit breaker" as applying to a device for the regular and usual interruption of an energized circuit as distinguished from a switch used only for opening circuits which are de-energized or not carrying load. This paper will consider only high-voltage oil circuit breakers, the term "high voltage" being taken as applying to potentials of 25,000 volts or above.

The fundamental purpose of a high-voltage transmission network is to deliver power with a maximum of reliability at a minimum expense.

The high-voltage oil circuit breaker is an integral part of a transmission network. It is purchased not to demonstrate whether or not it will fail under operating conditions, but to insure service under both normal and abnormal conditions.

In every paper on transmission line stability presented before the Institute during the past five years, the importance of fast and accurate switching has been emphasized. The present paper proposes to outline in a general way how present day high-voltage oil circuit breakers fulfil some of the operating requirements of transmission networks.

It may be said that oil circuit breakers are in use today only because no better substitute has been developed. In them, the function of the oil is to insulate the contacts one from another and from the tank or ground. Mineral oils with a relatively high flash point are the only insulating mediums thus far available. It must be noted, however, that during the time of arcing the oil is a decided detriment to the breaker. It becomes volatilized and builds up excessive pressures in the container, and it becomes ionized and forms a conducting path which aids rather than hinders the arc. If it were possible to so construct a breaker, it would be better to separate the contacts the required distance and then introduce the oil at the zero point on the voltage wave. This is not a practical possibility and it is therefore necessary to have the contacts immersed in oil at all times.

Many substitutes for oil have been proposed and tried with varying degrees of success, and of these a high vacuum seems to offer the greatest possibility of an ultimate solution to the problem.[2] A one-half inch travel of contacts in a high vacuum is equivalent to a great many inches of travel under oil, and many possibilities present themselves. The practical application of the knowledge is a real problem. An exceptionally high vacuum must be continually maintained under service conditions, and means must be developed for moving the breaker contacts the necessary inch or so within this vacuum before the switch can be made ready for general application. Of the other alternatives to oil, mostly hydrocarbons, which have been tried, none so far has been able to supplant the petroleum derivatives except for very special uses and even then only to a limited extent.

From the foregoing it is seen that there is no immediate prospect of using any current interrupting device for the control of high-voltage transmission networks other than the oil circuit breaker using a mineral oil as the insulating medium. It must therefore be the foundation upon which to base the immediate developments to secure improvements which will better fit it for the duties it must perform. That improvements are necessary and urgently needed is obvious to all operating men.[3]

The object of an oil circuit breaker is to interrupt current. For the purpose of this discusssion the characteristics of the interruption may be divided into two general groups, which may each be further subdivided for special consideration as follows:

- I Characteristics influenced by the operation of the oil circuit breaker.
  - a. Speed of break
  - b. Current (to a limited extent) to be interrupted.
- II Characteristics dependent upon the connected circuit.
  - a. Power factor,
  - b. Recovery voltage,
  - c. Phase balancing,
  - d. Growth and decay of current values,
  - e. Resonance.

The subheading, I-a, may be still further subdivided for a study of the manner in which the speed of break is controlled:

1. Assistant Engineer, Division of Hydroelectric and Transmission Engineering, Pacific Gas and Electric Co., San Francisco Calif.

Presented at the Pacific Coast Convention of the A. I. E. E., Del Monte, Calif., Sept. 13-16, 1927.

2. *Vacuum Switching Experiments at California Institute of Technology*, R. W. Sorensen and H. E. Mendenhall, A. I. E. E. JOURNAL, December, 1926, p. 1203.

3. A. I. E. E. TRANS., Vol. 43, 1924, pp. 656-657. and *Elec. World*, Feb. 5, 1927, p. 302.

See pp 1340-48 of Dec 1927 J. AIEE

I-a. Speed of break.

1. Speeding up moving parts by,
   a. Spring retracted contacts,
   b. Accelerating springs,
   c. Quick break contacts,
   d. Explosion chamber contacts.
2. Multiple breaks.

The manner in which the speed of break is affected by the several methods listed above will be considered as exemplified in present day operating practise.

a. Spring retracted contacts were first used extensively on oil immersed fuses which were in reality oil circuit breakers with a fuse as the tripping mechanism.

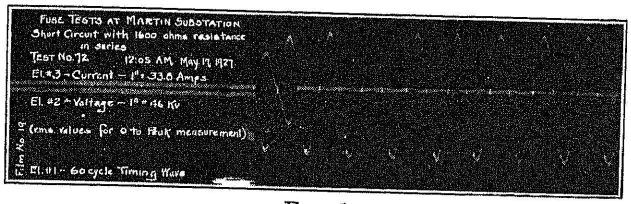

FIG. 1

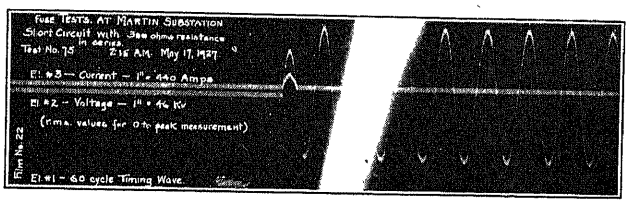

FIG. 2

They were developed and used in Europe prior to 1904 and have been thoroughly described in the technical journals of the time.[4] Letters patent covering this type of apparatus were granted in the United States in 1905.[5] This type of equipment is doubly interesting at the present time because the surviving examples represent at the same time the highest contact speed and the smallest physical dimensions of commercial current interrupting devices for use on high-voltage circuits. The speed of break attained in a 1½-ampere, oil filled spring retracted fuse with 7-lb. (3.17 kg.) pull is approximately 40 ft. per sec. (13.1 m. per sec.). An example of its performance with 1600 ohms resistance in series is given in Fig. 1 and with 300 ohms series resistance in Fig. 2. Both tests were made in the short-circuited phase to ground connection of a grounded Y 110-kv. circuit.

b. Accelerating springs are used at present on most of the high-voltage oil circuit breakers. They may be compression or tension springs or both, and in some cases both types may be found in the same breaker. Such springs are for the most part extended or compressed, (depending upon the type), by the final action of the closing mechanism of the breaker and serve both as a damping agent on the closing stroke and for acceleration of the contacts on opening. In certain cases, the contacts themselves serve such a purpose, as for instance in the Westinghouse butt contacts, which are spring-supported or the condit contacts which are of laminated leaf copper type. The effect of these contacts can be seen clearly in the accelerated travel of the moving member, which slows down again after the contacts part. See Fig. 6.

There are two major objections to the accelerating springs in general use. First, their effect is minor so far as a reasonable amount of speed in concerned, the maximum recorded being about one-half ft. per sec. (15.2 cm. per sec.); and second, they absorb energy at a time on the closing stroke when it cannot well be spared from most types of closing mechanisms. If greatly strengthened, they give rise to uncertain closing and hair trigger adjustments, already too much condemned by operating engineers to require further discussion. Suffice it to say that present day breakers require too many critical adjustments, and development must be toward a reduction in their number rather than any tendency to make them more critical.

c. Quick break contacts usually take the form of auxiliary contacts and serve two purposes,—first, to increase the separation betwen contacts in a given

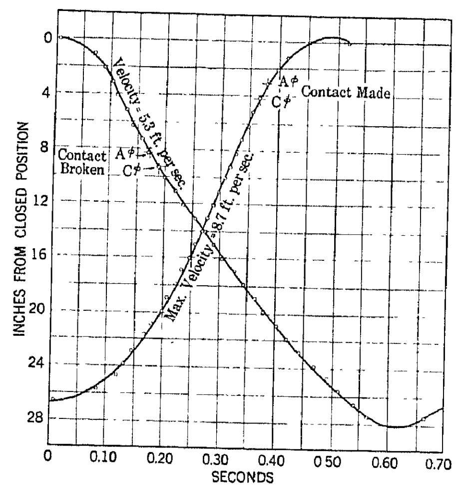

FIG. 3—CALIBRATION OF POSITION INDICATOR—110-KV., 400-AMPERE OIL CIRCUIT BREAKER

Vaca—Dixon Substation—June 20, 1926

time, *i. e.*, to reduce the time of arcing, and second, to preserve the main contact surface by breaking the arc on replaceable auxiliary contacts.

From an operating standpoint the time and energy required to operate the quick breaks is an advantage to the oil circuit breaker, gained at the expense of the system on which it operates. This comes about by reason of the fact that all varieties of quick break contacts now available delay the opening time until the contacts have traveled a sufficient distance to bring the quick break into action. Figs. 3 and 4 show the speed

4. *Elektrotech. Zeitsch.*, June 9, 1904, F. Collischonn.
5. Patent No. 781,347 to Christian Kramer, Jan. 31, 1905.

time curve of a Pacific Electric Manufacturing Company, 110-kv., 400-ampere, six-break, oil circuit breaker with contacts arranged as shown in Fig. 5. In this case, the main contacts part after 3 or 4 in. (7.5 or 10 cm.) of travel from the closed position, whereas the arcing contacts do not part until 8 or 10 in., (20 or 25 cm.) of travel has been obtained. This requires 0.075 sec. or more than 4 cycles on a 60-cycle system.

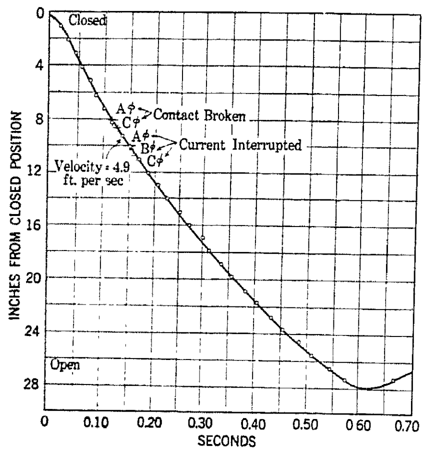

Fig. 4—Interruption of Pit Line Charging Current with 110-Kv., 400-Ampere Oil Circuit Breaker

Vaca—Dixon Substation—July 12, 1926

Fig. 6 shows the speed—time curve for a Westinghouse Type G-2, 187-kv. oil circuit breaker of the type used on a 220-kv. grounded Y system in which the quick break contacts have the form shown in Fig. 7. With this breaker, the main contacts part about 1½ in., (4 cm.)

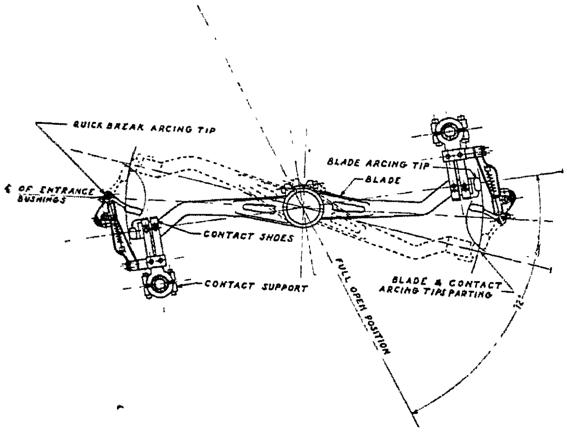

Fig. 5—Details of Contacts, Pacific Electric Oil Circuit Breaker

from the closed position and the quick break auxiliary contacts about 10 in. (25 cm.) from the closed position. This requires about 0.25 sec. or 15 cycles on a 60-cycle system. The speed obtained on the quick break contacts themselves is about twice that of the main contacts so that the arc when started is extended at about three times the main contact speed.

d. Increased contact speed may also be gained through the use of the explosion chamber type of contacts. These are a development of the original Type *H*

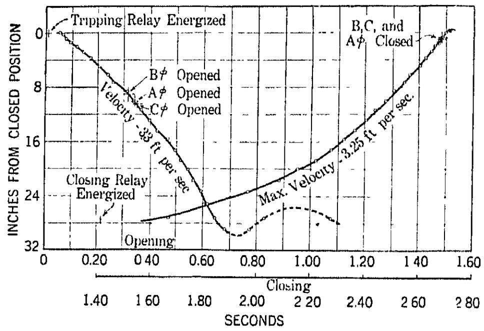

Fig. 6—Position Indicator Calibration

Westinghouse type G-2, oil circuit breaker, with rotating release arcing tips, at Vaca—Dixon Substation—June 26, 1926

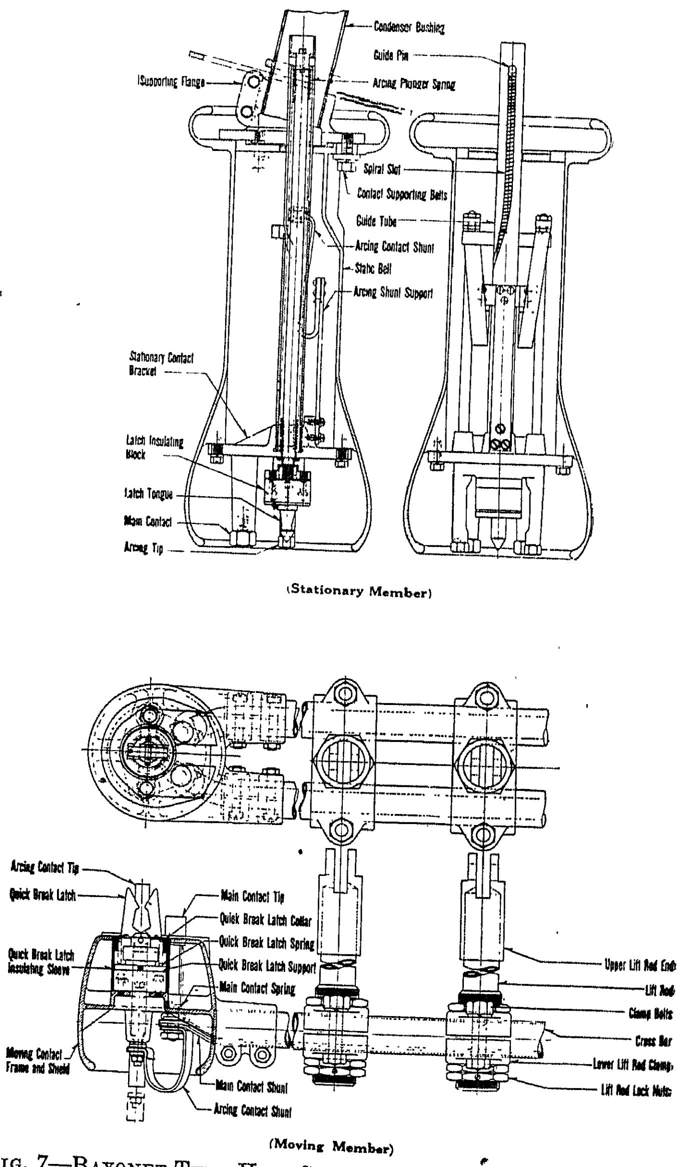

Fig. 7—Bayonet-Type High-Speed Contact (Rotary Form)

oil circuit breaker manufactured by the General Electric Company, and may be found in the high interrupting

capacity breakers of the General Electric Company in the United States, and its affiliated companies, notably the A. E. G., in Europe. The principle of the explosion chamber contact is illustrated in Fig. 8 and is too well known to require any extended description here.

In this type of contact the speed of break is obtained by virtue of the gas pressure in the contact chamber acting on the rod as a piston. The gas pressure is

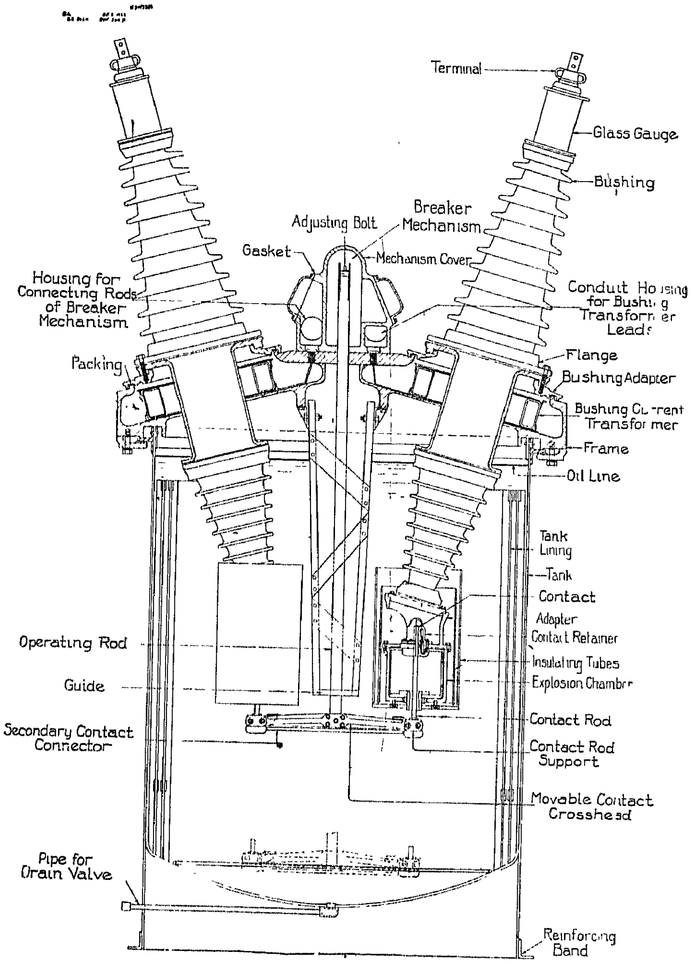

FIG. 8—TYPICAL OUTLINE OF SINGLE-POLE ELEMENT OIL CIRCUIT BREAKER, 110,000 VOLTS AND ABOVE

generated by the arc acting on the oil within the explosion chamber and depends upon the clearance between the contact rod and the explosion pot entrance bushing and the amount of oil volatilized. The amount of oil volatilized depends upon the current in the arc and the time of arcing. This means that high currents will cause increased contact speed over lower currents.

Fig. 9 shows the speed—time curve of a General Electric F H K O-36-33C, 115-kv., oil circuit breaker at no-load, and Fig. 10 shows the speed—time curves for the same breaker when interrupting 300 amperes of line charging current. In this type of contact the clearances are determined by the maximum amount of current to be interrupted and the maximum speed the contact member is permitted to attain. In the example given above, the maximum speed was 5.5 ft. per sec. (1.8 m. per sec.) while in the extensive Canton tests[6] the contact speeds were between 6 and 7 ft. per sec. (2 and 2.3 m. per sec.). The contact speeds attained at the Alabama Power Company tests[7] on explosion chamber breakers were between 4.75 and 6.6 ft. (1.56 and 2.16 m. per sec.). This type of breaker obtains increased contact speed at the expense of the oil in the circuit breaker.

The breakers thus far considered have all been of the two-break type, and the total length of arc in all makes is approximately the same. The contact speeds are also of the same order and range from 3.5 ft. (1.15 m.) per sec. to somewhat less than 7 ft. (2.3 m.) per sec. In order to better appreciate what these speeds represent, it may be well to convert them to mi. per hr., a term universally familiar to all Thus we see that 3.5 ft. (1.15 m.) per sec. is only 2.4 mi. (3.86 km.) per hr., 5 ft. (1.64 m.) per sec. is 3.41 mi. (5.5 km.) per hr. and 10 ft. (3.28 m.) per sec., 6.82 mi. (11 km.) per hr. which is only slightly above the speed of a brisk walk. Present day high-speed d-c. circuit breakers have a speed of approximately 200 ft. (65.6 m.) per sec.

Speed of contact travel is the only feature of the breaker which may be varied to reduce the time of arcing, and when it is considered that it is at present usual to ask for interrupting capacities of a million kv-a. or more, it would seem logical to greatly increase the

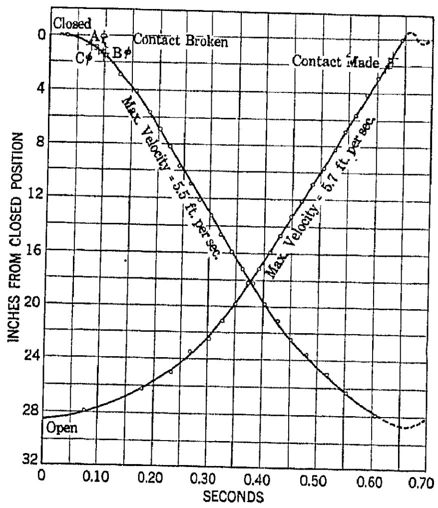

FIG. 9—CALIBRATION OF POSITION INDICATOR—115-KV., 400-AMPERE OIL CIRCUIT BREAKER

Vaca-Dixon Substation—July 10, 1926

speed of contact travel. The effect of increased contact speed will be discussed later.

Under the heading I-a, Speed of break, there still remains the consideration of the second subdivision, Multiple breaks. By common usage the term multiple break has been considered to apply to circuit breakers employing more than two simultaneous breaks in series

6. JOURNAL A. I. E. E. July, 1927, p. 698, *Tests on Oil Circuit Breakers*, by Sporn and St. Clair.

7. J. D. Hilliard, *Circuit Breaker Tests at Bessemer, Ala.*, TRANS. A. I. E. E., 1924, p. 636.

to interrupt the circuit. American manufacturers of this type of breaker are the Condit Electric Manufacturing Company (Brown Boveri type) the Kelman Electric and Manufacturing Company and the Pacific Electric Manufacturing Company. The Brown Boveri switch tested at Canton[8] was an imported breaker, but almost identical with the American built breakers of the same design. This was a type A F 24/1A, 150-kv. breaker with ten breaks in series per pole. It had a contact speed of from 1.7 to 2.2 ft. (0.56 to 0.72 m.) per sec. and a contact travel of a little less than one foot, (0.3 m.).

The Pacific Electric breaker has six breaks in series per pole, the contacts rotating to make a horizontal break. The speed—time characteristics of this breaker with a solenoid operating mechanism are shown in Fig. 4. The most recent switches of this company are equipped with a motor-wound spring-type operator which has increased its speed of operation to give a contact travel of approximately 15 ft. (5 m.) per sec.

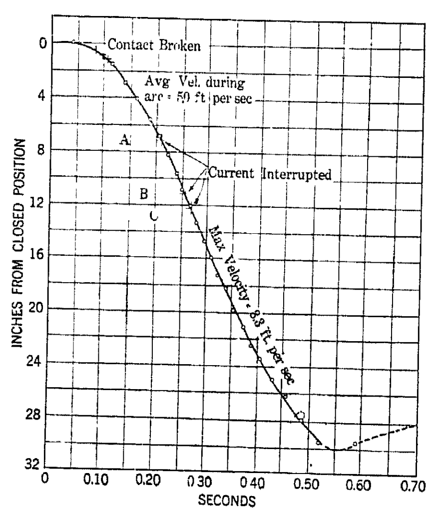

Fig. 10—Interruption of Pit Line Charging Current with 115-Kv., 400-Ampere Oil Circuit Breaker

Vaca—Dixon Substation—July 10, 1926

with speed—time characteristic curves of the same shape as shown in Fig. 4.

Kelman breakers also employ a six-break contact which is controlled through a pantograph mechanism to make a horizontal linear break. The breaker is solenoid operated, and has a contact travel of approximately 3.2 ft. (1 m.) per sec.

The importance of speed in clearing trouble in a high-voltage transmission network cannot be too strongly emphasized. As systems grow in size and the amounts of power available at a fault increase, it becomes more and more necessary to isolate the fault in the shortest possible time. With the large amounts of power available, great damage is done in a very short space of time and the very existence of the network depends upon the quickness and accuracy of the switching.

Relays have been developed and applied to line protection to such an extent that it is now practicable to relay a line so that troubles causing a flashover can be cleared before material damage is done to the line insulators or conductor more than 90 per cent of the time. Relays are now in operation which will close their contacts selectively on grounds on one of a pair of parallel lines in a definite direction on both ends of that line in considerably less time than is required for any available high-voltage oil circuit breaker to open its contacts after the trip coil has been energized.

It will be shown later that the time required to open the contacts of a present day high-voltage oil circuit breaker is roughly one-half the total time required to clear the average case of trouble. Exception to this is made in the case of the breakers with explosion chamber type contacts where the time is greater or less dependent upon the particular design and the current to be interrupted. It is therefore evident that the time consumed by the relays in discriminating between circuits and starting the necessary operations to trip the switch is approximately only one-third of the total time required to clear the circuit. The balance of the time is taken by the oil circuit breaker itself in completing the interruption and is unnecessarily long. That increased speed is desirable seems to be universally accepted. The best method of achieving this increased speed seems very much debated. From an operating standpoint, however obtained, higher interrupting speeds would benefit both the breaker itself and the system of which it was a part.

Limitation of Current

In the foregoing outline under subheading (b) as a characteristic of the circuit interruption influenced by the oil circuit breaker was given the limitation of the current to be interrupted.

In such breakers as have this feature incorporated, it is usually accomplished by the insertion of resistance into the circuit before the final rupture takes place. European breakers use this feature much more often than those manufactured in America, one reason being that the greater proportion of European oil circuit breakers are multiple contact and lend themselves particularly well to such treatment.

The mechanical design of high-voltage oil circuit breakers is not yet advanced to a point where the resistance feature can be added without reducing the mechanical reliability of the breaker below a safe minimum in many cases.

However, low-voltage circuits for heavy duty are customarily equipped with external reactors to reduce the duty on the oil circuit breaker and are considered sound practise even though they entail a continuous loss often for the sole purpose of protecting the oil circuit breaker momentarily during trouble.

8. Sporn and St. Clair., *Tests on Oil Circuit Breakers*, Journal A. I. E. E., July, 1927, p. 698.

The expense and operating difficulties attending the use of external reactors for high-voltage work has prohibited their use for 60 kv. or above, except in a few isolated cases. The mechanical difficulties attending their use internally on a two break oil circuit breaker have likewise prohibited their use in that direction in this country.

CHARACTERISTICS DEPENDENT UPON THE CONNECTED CIRCUIT

As subheadings under those characteristics over which the oil circuit breaker has no control are grouped: (a) power factor, (b) recovery voltage, together with others to be considered later.

Because of the fact that the current in an a-c. circuit is broken at or near the zero of the current wave the duty on the breaker is least at unity power factor since the voltage across the contacts is also zero at that time. With a decrease in power factor two things happen:

First: The voltage available to strike across the gap and reestablish the arc is higher being a maximum at or near zero power factor since the voltage is a maximum when the current is zero at that time.

Second: Since the character of the circuit interrupted determines the character of the voltage wave across the contacts, the arc voltage on inductive circuits has the characteristic horns as discussed in many texts.[9]

These horns for metallic electrodes under oil are very sharp, frequently too sharp to be recorded satisfactorily on the commercial oscillograph and are often equal to or slightly greater than the nominal circuit voltage at the time of interruption.

Contrary to the usual idea, system stability tests have demonstrated that in practise the power factor of a ground on a high-tension network may have been reasonably good and operating practise has determined also that by far the major portion of high tension network troubles are from conductor to ground.

In practise, therefore, the power factor of the circuit, while important, is not vital to an oil circuit breaker with any reasonable margin of safety except in special cases which will be considered later. Coupled with power factor is recovery voltage usually defined as the voltage across the oil circuit breaker contacts in the first half cycle after the circuit is interrupted.

The only thing definitely established regarding recovery voltage on an operating network is that it is not the simple vector relation of normal voltages that a single generator gives on test. All of the transient characteristics of the connected equipment influence it sometimes for several cycles after the arc has cleared.

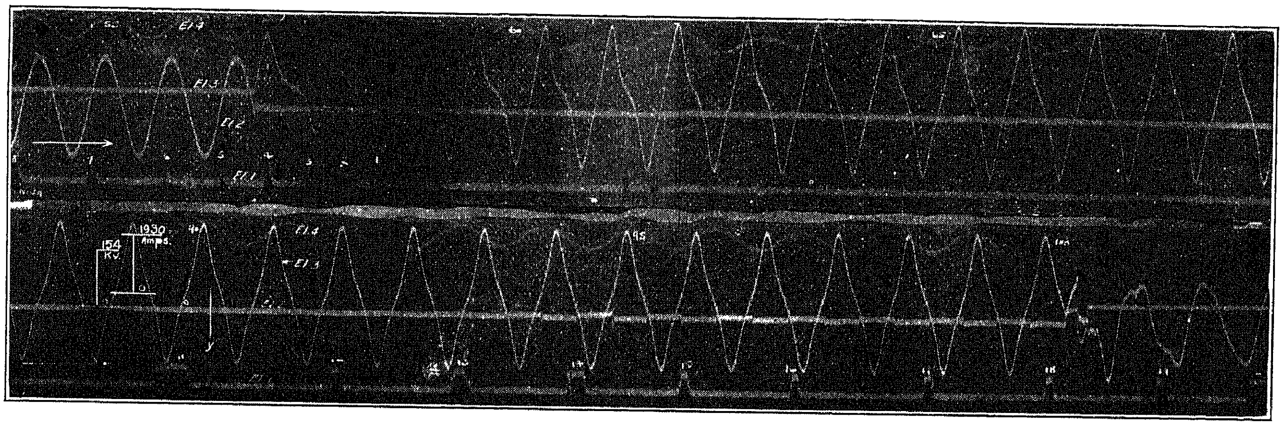

FIG. 11—INTERRUPTION OF SINGLE-PHASE GROUND ON PIT LINE NO. 1 (SYSTEM CONNECTED)

Vaca—Dixon Substation—July 9, 1926
Y — B P contacts open
El. 1—Position indicator
El. 2—Arc volts B phase
El. 3—B phase current
El. 4—50-cycle timing

PHASE BALANCING AND GROWTH AND DECAY OF CURRENT VALUES

In low-voltage networks and particularly in oil circuit breaker tests on a single generator the current to be interrupted begins to decrease after the first half cycle of short circuit. It is therefore, as a rule, easier for the oil circuit breaker to clear the circuit several cycles after the short circuit is applied.

Most troubles on such generators and networks are between phases so that such tests represent a practical operating condition.

High-voltage network troubles are more often from wire to ground; on the sytem of the Pacific Gas and Electric Company for instance, on 60 kv. and above, over 95 per cent of all line trouble is from phase to ground. For such conditions the initial short circuit current may be only a fraction of the final value to be interrupted.

Fig. 11 gives an oscillograph record of a wire to ground short circuit on one of two parallel 220-kv. lines with the system in normal operation cleared by relay in the

9. Alternating Current Phenomena, C. P. Steinmetz, Pages 353-357.

usual way, leaving the second line in service. The current in this case increased for some 5 or 6 cycles and was then practically constant until interrupted. This is due to the so-called phase balancing action and in some cases has given as high as a 2 to 1 ratio between initial and maximum amperes. The same thing takes place if the several phases of an oil circuit breaker do not interrupt the circuit simultaneously although this trouble is largely eliminated from present day oil circuit breakers.[10]

Resonance

Of all the phenomena occurring during the interruption of a high-tension circuit as part of an operating network, there remains the one probably the least understood,—resonance. At the instant the contacts part, an arc is established. It has a so-called negative resistance due to the fact that the initial stream of ions and electrons under the influence of a high potential gradient cause additional ions and electrons by collision. This in effect increases the area of the arc and decreases the resistance.

At the start of the break there is a relatively low potential across the arc and the effect of arc voltage is scarcely noticeable. As the contacts part the voltage across the arc increases and the current growth for each cycle is determined more and more by the characteristics of the connected circuits frequently differing greatly from the system frequency.

This ability of the arc to convert from one frequency to another is well known in communication but is little appreciated by transmission engineers and practically no data on the effect of series arcs in a circuit containing capacity and reactance are available.[11]

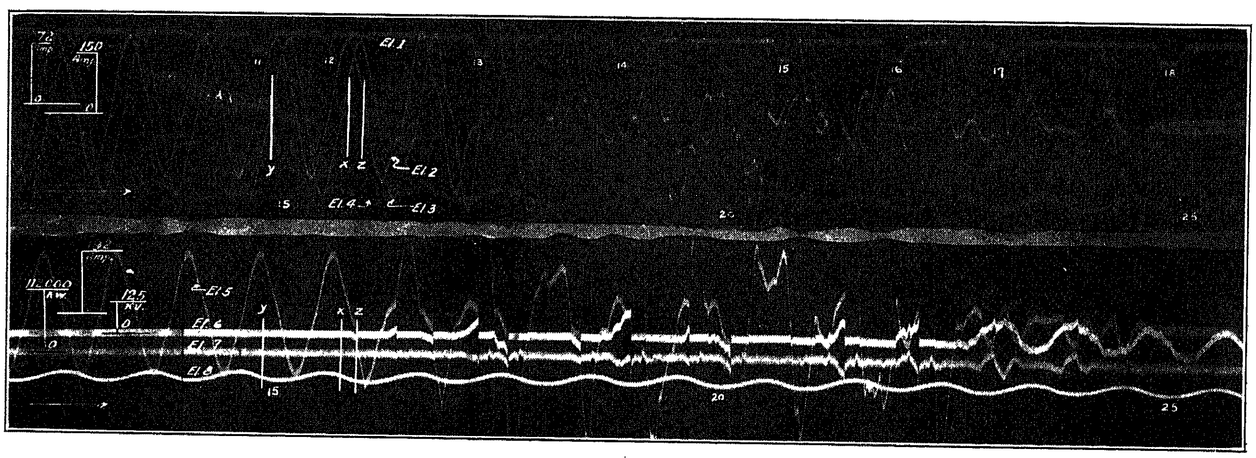

Fig. 12—Pit Line Charging Current Interruption at 220 Kv.

Vaca—Dixon Substation—June 26, 1926

X—A-phase contacts open
El. 1—Position indicator
El. 2—C phase current
El. 3—A phase current
El. 4—50-cycle timing

Y — B phase Z — C phase
El. 5—B phase current
El. 6—Arc volts B phase
El. 7—Arc watts B phase
El. 8—50-cycle timing

This has an immediate and practical application in high-tension oil circuit breaker practise because on every line that is cleared in trouble to ground at least two phases at one end must interrupt charging current which may or may not be the nominal charging current of that line.

In Fig. 11 was given a record of the interruption of a single-phase 220-kv. ground of some 2430 amperes.

Fig. 12 gives the record of the same oil circuit breaker on the same 202-mi. line interrupting 156 amperes of charging current at 220 kv.

The length of arc, slightly under 19 in. per contact, was the same, the contact burning the same so far as visual inspection could determine, and the deterioration of the oil the same. Figs. 13 and 14 give these plotted in the form of curves.

It is to be noted that after the first two cycles the current builds up at the natural period of the line to values much in excess of the normal 60-cycle charging current, the speed of current growth being greater for short sections of line since the characteristics change for them.

In practise such records have been taken for several makes of 110-kv. oil circuit breakers for identical conditions using the several methods of increasing contact speed from two break breakers with a speed of less than 4 ft. per sec. per contact to 6-break breakers with a speed of 15 ft. per sec. per contact and a range of arcing time from 12 cycles on the slower speed to 2 cycles on the higher speed.

The total arc length increases for a given duty on most types as the speed increases at some rate less than the speed increase, *i. e.*, a 6-break oil circuit breaker has a greater total arc length, but a much shorter length per

10. *Practical Aspects of System Stability*, R. Wilkins, A. I. E. E. Trans., Vol. XLV, 1926, p. 41, (Fig. 7).

11. C. P. Steinmetz, *Frequency Conversion by third Class Conductor*, A. I. E. E. Trans., Vol. XLII, 1923, p. 470.

contact than a two-break oil circuit breaker for the same duty.

The important point often overlooked is that the high-speed breaker clears the disturbance in much less time with much less damage both to the system and to the breaker.

There is no virtue in making an elaborate contact arrangement and then slowing the whole mechanism down to the same total speed as a simple one break breaker. But a breaker which will clear a given trouble in one or two cycles is a much more satisfactory piece of apparatus than one requiring 15 cycles, provided it can be properly relayed and made to stay together.

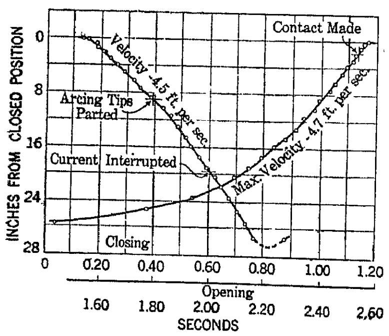

FIG. 13—SINGLE-PHASE GROUND ON PIT LINE NO. 1

Equipped with rotating release arcing tips. Breaker tripped out by station relays. Line connected to System, at Vaca—Dixon Substation—July 9, 1926

CONCLUSIONS

Throughout this paper the viewpoint on controversial subjects has been from the practical side; that is to say, from the position of the operating man rather than the manufacturer. This as is it should be, for design must meet the requirements of the operating man who purchases and uses the apparatus.

The primary assumption has been made that the function of a transmission network is to deliver power with a maximum of reliability at a minimum expense. The oil circuit breaker is an integral part of the network and has a particular and very important function to perform.

Engineers engaged in the design of transmission networks must now plan the network to operate in such a manner that it will not overstep the capacities of the oil circuit breakers installed. These capacities are not definitely known and therefore large factors of safety must be allowed and unnecessary expense incurred.

This is especially true in very high-voltage transmission lines, where both carrying capacity and stability are greatly improved if the lines can be broken up into sections by switching stations and only a relatively small section isolated to clear up trouble. Such a plan is not generally carried out because of the operating limitations and great cost of high-voltage oil circuit breakers. The oil circuit breaker is therefore the limiting feature to the securing of the best possible operating results in electric transmission developments involving many millions of dollars.

With the increase in transmission voltage and the large concentrations of power, there has come a new set of problems not previously encountered. The problems of transmission line stability and continuity of service are of the utmost importance because outages render large blocks of power unproductive of revenue and may cause financial loss to consumers dependent upon continuous service. The position which the oil circuit breakers hold in these problems is becoming more generally realized, their faults and shortcomings recognized and most important of all, their economic relation to the rest of the development is being clarified. This has taken time, for engineers and operators have formed the habit of unconsciously basing their decision around oil circuit breaker limitations. They had to be on the safe side, and what would have been the best solution of a problem may have been discarded in place of a plan less favorable from economic or operating results, but more sure of success because the circuit breakers could not be considered as highly reliable pieces of apparatus to guarantee the carrying out of the most desirable plan.

Certain fundamental requirements may be set down as essential in an oil circuit breaker for use on high-voltage transmission networks. To meet these requirements with present day knowledge of oil circuit breaker design requires a composite breaker embodying the strong points to be found in the designs of the several manufacturers. Briefly, these requirements are:

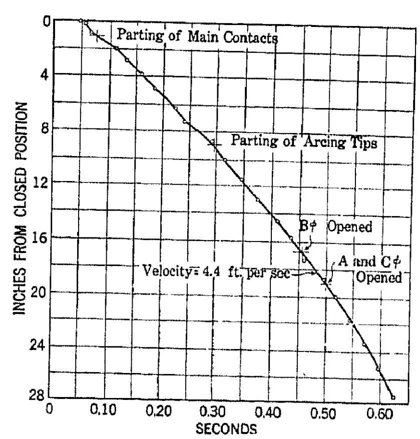

FIG. 14—PIT LINE NO. 1 CHARGING CURRENT INTERRUPTION, WITH WESTINGHOUSE TYPE G-2 OIL CIRCUIT BREAKER

Equipped with rotating release arcing tips at Vaca-Dixon Substation, June 26, 1926

1. The total operating time for a complete "open-close-open" cycle of operations at rated current, and voltage shall not be more than 0.2 sec.

2. The arcing time shall approach as close as possible to the ideal of one-half cycle.

3. The energy for the switch operator shall be stored and available for instantaneous release. The mechanism should not have a power demand in excess of one kw.

4. The breaker shall be capable of completing 100 normal operating cycles before any inspections or adjustments are necessary. (If requirements 1 and 2 are met successfully, there should be no trouble in reaching 1000.)

5. The breaker shall be so designed that it can be installed, adjusted, and maintained by the average mechanic without especial training in oil circuit breaker technique.

The growing knowledge of the important part played by the oil circuit breaker in a transmissiion network is stimulating investigations on the part of the operating companies to satisfy themselves as to the best circuit breaker for use on a given system. As has been previously stated, it is economically unfeasible for each manufacturer to maintain equipment for the testing of oil circuit breakers with a rating of 2,000,000 or more kv-a. at 220,000 volts. Also these tests at the manufacturers' plants are not conclusive for it is impossible to duplicate the conditions met on an extensive, interconnected transmission network, where recovery voltage, resonance, surges, etc., are variable and indeterminate.

The only way in which it is now possible for an operating company to satisfy itself of the suitability of any theory of circuit breaker design, is to conduct carefully supervised tests on its own system. This requires a maximum of courage, but if reliable service is the ultimate goal, all equipment must be tried and found not wanting. Competitive designs and theories, coupled with a wide range in price quotations, all in the face of a positive refusal to give any guarantees on performance, make the selection of an oil circuit breaker for a given installation extremely difficult. Present day knowledge must be amplified by further test data.

It is entirely possible that the oil circuit breaker as now known, may not be the ultimate device for opening a-c. circuits. They are used today because they are the only devices which have been developed to the point where a reasonable dependence may be placed on their operation.

The immediate problem is to combine in one oil circuit breaker all of the good features now available in the designs of the several manufacturers. By so doing it will be possible to approach the operating requirements set down previously, and secure a breaker superior in performance to any now offered. Along with this must go continued research, looking toward the development of a device for the interruption of a high-voltage, a.-c. circuit which will be as dependable in its operation as is the transformer and generator. Pending this time, oil circuit breakers must be purchased and used with a full knowledge of their limitations.

Discussion

J. D. Hilliard: In this paper the importance of high-speed switching in increasing the stability of the transmission network is emphasized, and the conclusion is drawn that the oil circuit breaker is the only piece of dependable apparatus at present obtainable, or likely to be obtainable in the near future which can be used for this work.

To this conclusion I think no exception will be taken by those familiar with the operation of interrupting devices for electric circuits, including the so-called vacuum switch.

For years it has been recognized that speed was one of the chief factors in the construction of an efficient oil circuit breaker, but it was also recognized that the oil breaker must be of sturdy construction. By speed I mean the total time elapsing between the beginning of the short circuit and the complete interruption of the current.

The fact that one breaker may have a shorter arcing period than another may be of small moment so far as system stability is concerned, if the total interrupting period of the two breakers is practically identical, and when test data are given both the total short-circuit duration and arcing duration should be given, if a logical comparison is to be made.

Whether a shorter arcing duration is favorable to one breaker as compared to another breaker will depend on the speed of break (per break unit) of the two breakers, and the number of breaks in series; in other words, it will depend upon the total quantity of gas generated in the two breakers.

Tests with plain-break contacts, operating under identical conditions, have shown that the two-break breaker is quite likely to generate less gas than 6, 8, or 10 breaks in series. It is a fact as the authors have pointed out, that a current-limiting resistance in series with the arc, greatly reduces the severity of the arc. This coupled with the light weight and high speed of the moving parts explains the superior action of small potential fuses where the current flow is limited by resistors. When, however, an attempt is made to apply the same kind of a device to an oil circuit breaker where the resistance must be shunted in circuit when the breaker operates, it is found that many difficulties arise, not the least important of which is keeping down the cost of the breaker equipment.

The authors have given the speed of a General Electric Company FHKO-36-33 C, 115-kv. oil circuit breaker as 5.5 ft. per sec. maximum at 300 amperes charging current. The interrupting capacity of this breaker for two O-C-O duty cycles is 3750 amperes at 115,000 volts, and since the speed of operation of this breaker is a constant of about 5 ft. per sec. at no load, plus a variable dependent upon the load interrupted, the figures given, although correct for the quoted load, are not half their real value when the breaker is interrupting its rated interrupting capacity.

Moreover, one can expect a longer arc when interrupting a small charging current than that obtained when interrupting the full interrupting capacity of the breaker, so that taking both these factors into consideration, one would expect the full-rating arc duration would be less than half as long as the charging-current arcing duration.

It is also a fact that the speed of operation of the explosion-chamber breaker is a maximum shortly after the end of the contact rod clears the throat bushing,—that is, the speed is a maximum at the time of the long arc, and this means the smallest quantity of gas during that period. This should be compared with the breakers having the maximum spring tension and maximum speed during the early stages of arcing when the gas generated per unit of arc length is small. In one case we have a maximum speed decreasing to a minimum; in the other case we have a minimum speed increasing to a maximum.

The quantity of gas generated at constant speed of contacts for a given arc duration varies approximately as the square of the speed, because the arc likewise varies directly as the speed.

When the above facts are considered, it is easily seen why the explosion-chamber breaker produces such a small quantity of gas, and why it has such a high interrupting capacity.

It is not clear to the writer why high speed of separation is

necessary when interrupting line charging current or load currents of small magnitude, because under these conditions the line should be fairly stable.

For heavy short circuits, however, high speed would be advantageous, and it is under these conditions that the explosion-chamber breaker is at its best, and its strong construction enables it to stand repeated interruptions without damage.

The Canton tests were 26 and 30 consecutive operations on the two breakers, without examination of the oil or contacts, and both were in first-class condition at the end of the tests and could, undoubtedly, have duplicated the performance and still have been in good operating conditions. It is probable that 100 such operations would still have found them able to carry their rated load and interrupt their full rated interrupting capacity.

It is to be expected that the earlier explosion-chamber breakers would not be developed to the degree found in the modern breakers, that the years of operating experience would result in breaker improvements, that better constructional methods, better materials, and better workmanship would be built into the later breakers just as there have been improvements in the automobile in the same period.

It is unfortunate that the various curves mentioned in Messrs. Wilkins and Crellin's article are not available at this time, and, therefore, no comparison can be made on the time of relay action, breaker trip, and breaker interruption of circuit.

In the article no mention is made of tank pressures as a function of speed of interruption, and but little has been said concerning voltage rises due to the same cause.

Fairly high impact pressures must be expected in the oil when high-speed interruption takes place, although at the time there may be no evidence of pressure in the air space above the oil. This high impact pressure is due to the substantial incompressibility of the oil, the mass of the oil and the instantaneous generation of a gas in fairly large volume. It acts, of course, to stress the tank and unless the seams are well made, may result in their being opened up, whereas with a slower operating breaker the stresses may be considerably less.

The voltage rise, from substantially instantaneous interruption, is likely to be a real problem, and in such apparatus excessive voltages have been observed during tests, and the steep wave front makes it impossible to obtain an oscillographic record with the ordinary oscillographic apparatus.

Peak records can, of course, be obtained by a surge recorder, or by the cathode ray oscillograph, and such records have shown surges considerably in excess of any mentioned by the authors. It is not impossible that under special conditions, voltage surges of 25 times the applied volts may be observed.

The authors mention the fairly high power factor in a short circuit to ground. This is, of course, due to the ground resistance and was to have been expected. It also largely accounts for the fairly easy condition for ground interruption on a system having a grounded neutral. The fundamental requirements, as laid down by the authors, are not so impossible of achievement by the high-voltage oil circuit breaker as would appear at first glance, and with the exception of (1) *i. e.*, O-C-O cycle of operation = 0.2 second, can I believe be approximated if there is a demand for such a breaker and the purchaser is willing to pay the price of development.

The testing of oil circuit breakers by the manufacturer and user is of great importance, and the General Electric Company's engineers are not only making such tests daily at the factory, but have taken every opportunity to make tests upon operating systems.

The General Electric Company strongly recommends the publication of full detail information on such system tests. Such information will be of incalculable value to transmission companies and manufacturers of oil circuit breakers, and will act largely to dispel the skepticism concerning circuit-breaker operation and rating which now exists. The factory tests are considered of so great importance that a new testing generator has been constructed and will have been given preliminary tests by September 10, 1927.

This generator is the largest testing generator ever constructed, and is expected to give a short-circuit kv-a. of nearly 600,000. Space has been provided for additional generators of the same or larger capacity, and it is expected that if connected to the Mohawk-Hudson system ultimately a short circuit capacity of considerably in excess of 1,000,000 kv-a. will be available at both low and high voltages.

The testing installation has been made very complete, and comprises both resistors and reactors for current limitation, bomb-proofs in which to test the breakers, a separate oscillograph and assembly building and ample grounds surrounding the test plant, so that the test men and observers may be at a safe distance from the breakers tested to destruction, and every breaker which can be stressed to that extent will be so tested. The testing equipment will, of course, be as complete as it can be made, and instruments are provided for measuring all factors affecting the interrupting capacity of the breakers that it is possible to measure.

In the thousands of tests made with our factory testing generator during the past six years, we have observed phenomena far more severe than any ever recorded by us on tests made upon transmission systems. We have observed arc lengths in excess of the charging-current arc lengths observed by the authors; and it is my opinion that our testing conditions are more severe than obtained on any transmission system in existence today, if we except the operation of a transmission system at the instant of a lightning stroke.

These observed test values are used in the design of new breakers, and it is these observations which determine the physical dimensions of our breakers. It is because of our observations that the break distances of General Electric breakers are made consistently greater than those of any other manufacturer; and although we realize that it may be a rare occurrence for an arc to be drawn the full break distance, it is also realized that a sustained arc in an oil circuit breaker is a serious thing and may result in the destruction of the breaker, and must be guarded against at any cost.

The authors state that the manufacturers positively "refuse to give a guarantee on performance." I think that a consideration of the facts will show that statement is not exactly correct. While the General Electric Company does not guarantee their breaker rating, they do stand back of their breakers and will continue to do so.

At a joint meeting of the Oil Circuit Breaker Section of the Power Club and the Oil Circuit Breaker Subcommittee of the N. E. L. A. a year ago, all of those present were unanimously agreed that a manufacturer could not guarantee interrupting capacities of oil circuit breakers, because the interrupting capacity at any given instant depended on system, maintenance, and operating conditions which were entirely beyond the control of the manufacturer.

The Oil Circuit Breaker Subcommittee of the N. E. L. A., therefore, unanimously agreed that three alternative clauses be recommended to the manufacturers, but expressing a preference for the following clause:

"Because system, maintenance, and operating conditions are beyond the control of the manufacturer, interrupting capacities of oil circuit breakers cannot be guaranteed, but this does not relieve the manufacturer of his contract obligation to deliver oil circuit breakers having interrupting capacities as specified."

Acting on this recommendation of the Oil Circuit Breaker Subcommittee of the N. E. L. A., the General Electric Company adopted this clause as recommended. Under this clause, the company is bound by a legally enforceable contract to deliver a circuit breaker having the specified rating, and evidence that

the circuit breaker does not have the rupturing capacity specified would force the company to replace the circuit breaker with one having the specified rating, or would make the company liable for damages for breach of contract.

There may be uncertainty in the minds of some manufacturers and some users as to the meaning of kv-a. interrupting capacity. Is it the interruption at unity power factor, or at approximately 90 deg. lag or lead? Is it the interruption of the current on an otherwise isolated bus system, or is it interruption on a system having a connected load with shunt reactance and electrostatic capacity? Is it on grounded or ungrounded systems?

As far as the General Electric Company is concerned, and based on engineering information that has become available from field and testing department experience, the General Electric Company's published interrupting rating includes all the conditions mentioned above and the General Electric Company will continue to publish ratings on this basis unless future development makes modification necessary, in which case, the published ratings will state that fact.

The writer regrets that the tests did not include repeated interrupting tests at or near the rating of the breaker so that observations of contact burning could have been made.

H. E. Strang: In discussing oil circuit breakers the term "Speed of Operation" is frequently used and unfortunately at times loosely applied with the net result that some confusion exists as to just what thought this expression is intended to convey.

From the standpoint of system stability, interest is centered around the total time required for opening a circuit from the instant the trip coil is energized until the arc is finally broken, rather than the actual speed in feet per second at which the contacts may part.

An analysis of the opening characteristics of various kinds of breakers will reveal the fact that one type of motor operator which imparts a comparatively high speed in terms of feet per second to the contacts after they have started moving, has an inherent time delay in the tripping mechanism itself, which makes the dead time, or the time from energizing the trip coil until the contacts part, nearly twice as long as in the case of breakers operated by other types of motor or solenoid mechanisms.

Supposing that there may be a balance in favor of the breaker operated by this former mechanism of some few half cycles of arcing time, the total duration of short circuit may be much longer than in the case of a breaker whose contacts travel more slowly, but operated by a mechanism with a shorter inherent dead time. It is this feature which is essential when considering the application of oil circuit breakers from the standpoint of their effect on system stability.

It is regretted that the curves which have been presented showing the opening characteristics of various types of breakers were not plotted on the same basis, that is, from the time the tripping impulse is delivered to the trip coil.

Figs. 9 and 10, showing the opening time of a General Electric FHKO-36-110-kv. breaker seem to answer a commonly raised question regarding the effectiveness of explosion chambers at low currents. In this case while opening only 300 amperes which is some 8 per cent of the breakers' interrupting rating, a definite acceleration is given to the contacts which amounts to an increase of about 2 ft. per sec. in maximum velocity over the no-load speed.

That this effect is consistent in reducing the arc length over the entire range of a breaker's rating is also apparent from the published results of the Canton tests where in the case of one explosion-chamber breaker during a series of 30 tests, ranging from 23 per cent and 83 per cent of its interrupting rating, the arc length varied from but 40 per cent to 20 per cent of the stroke.

As the authors have stated, the ultimate interrupting capacity of these large breakers may not be definitely known. It is believed, however, that if there is any uncertainty in the ratings it is on the side of conservatism, and that it is not necessary to apply factors of safety to the ratings of breakers which have been subjected to extensive factory tests, the results of which have been substantiated by field tests such as those made at Canton.

M. M. Samuels: May I be permitted to add some constructive suggestions? First is the question of the parts which the users and manufacturers should respectively take in the further development of breakers.

Now, it is not possible, nor is it necessary for an operating man to known as much about all of the detail problems of breaker construction as a manufacturer's engineer. But the operating man knows what he wants the breaker for, what service it has to perform, he knows this better than the manufacturer; he has to make it perform as part of a system, and he soon finds out wherein it fails so to perform.

Advice along these lines from operating men should be eagerly sought by manufacturers. The manufacturer should realize that the customer is not just kicking for the fun of it; but that when he kicks there is something wrong; and then let the experts get busy and find out what is wrong.

The needed spirit of cooperation on the part of the manufacturers is beginning to show itself here and there, and has no doubt been a contributing factor of considerable importance in the great strides which the manufacturers have made in very recent years in circuit breaker developments. But more of it is needed.

Another suggestion which may be made is that future tests should be carried on under actual operating conditions. So far, elaborate preparations have been made for each test. Contacts were cleaned and adjusted, mechanisms greased, relays cleaned, new oil placed in the tanks, etc. Under operating conditions this is not done every day, and in most cases it is not done often enough; and yet breakers have to operate.

I should suggest that in the future tests be made on breakers after they have been in service for some time, without making such preparations. In other words, without telling the breakers that they are going to be tested.

As to the concluding requirements of Messrs. Wilkins and Crellin, I may state that the one requiring a maximum of one kv. is to my mind not of great importance. I will grant that the great amount of power required to close some breakers is due to very clumsy mechanism designs. The bell-crank artist is still among us, and the manufacturers have not as yet learned that a good switch designer is not necessarily a good mechanism designer, and that none of the switch mechanisms shows the ingenuity and beauty which may be observed in some of the automatic machinery which they have in their own shops. However, give me a good breaker, and I do not care if it takes 5 kw. to close it.

The suggestion that it should be possible to install a breaker without skillful mechanics likewise seems to be going somewhat too far at the present. It is true that breaker mechanisms should be simplified rather than be made more complicated; but I doubt if it ever will be possible or even desirable to eliminate the skillful mechanic in the installation of breakers.

Let me add a concluding remark. It will be necessary to reduce the cost of breakers in the future. The breaker today represents the limit to electrical development, not only insofar as it sets a maximum to the amount of energy that can be safely switched, but also economically. Many a prospective development cannot be put through because the cost of switching makes the whole development uneconomical. It will not be sufficient in the future to spend half a million dollars on research to find out that the tank steel has to be ½ in. instead of ⅜ in. thick, and to spend another half million to find out that two more pounds of copper will have to be added to the contact, or that structural-steel tops are in some cases preferable to cast-steel

tops. To our shame it must be admitted that the ratio of results to development expense is very low in the circuit-breaker field, and it is development expense which makes the cost of breakers so prohibitive.

Radical discoveries and inventions are needed, if the industry is to progress. A beginning has already been made, and one hint is already mentioned in the paper as to what might be expected in the future. I am referring to vacuum switching. But so far that is only a hint; and in general there are very few inventions of ingenuity and importance on record in the whole history of switching.

The industry seems to have been immunized against an attack by the bacillus of invention. Messrs. Wilkins and Crellin are right, therefore, in their statement that we are doomed to depend on oil breakers for a good long time to come; and that the improvement of them, to which I may add the reduction of their cost, is of immediate importance.

L. C. Williams: "Speed" is a much misinterpreted word. The electrical engineer talks in terms of cycles for interrupting a circuit or clearing a fault whereas the mechanician speaks in terms of velocities of the moving elements.

Let us consider switching time in two parts, (1) the time required to overcome inertia and acquire acceleration of blades and measured from the time the relay contacts close until the arcing tips separate and (2) from that point until the arc is broken and the fault cleared.

The sum of the two times is important from the standpoint of system stability and all operating engineers desire it cut to an absolute minimum.

The second consideration is of vital importance in switch performance as high blade velocities contribute to a short duration of arc and improvement in switch reliability.

Our present methods of control work somewhat at cross purposes. To gain high blade velocities is usually at the expense of burdensome control equipment and markedly increasing the time to get under way.

What we want is an improved control equipment which permits the switch to operate rapidly and minimize the overall operating time.

Slow-motion pictures taken of the mechanism of heavy duty switches emphasizes this necessity and likewise afford an accurate means of calibrating switch speed curves.

W. S. Edsall: The paper points out the desirability of clearing trouble from the transmission line in the shortest possible time. Several curves are given showing oil circuit breakers of the 110,000- and 220,000-volt class, giving the time required from closed position to the contact-breaking point and arc-clearing point. It is noted that on one 110,000-volt contact-break type of breaker it required about 0.125 sec., or 7½ cycles on a closed position to opening of the contacts. About 4½ to 5 cycles additional were required to break the arc of the changing current. Contrasted to this in a desire to point out that records are available showing the performance of the American Brown Boveri Electric Corporation BO-60, 110-D oil circuit breaker handling short circuit in the order of 400,000 kv-a. where the complete O-C-O cycle was made in approximately 14 cycles. This time is taken from the instant the contacts touched on closing plus the relay action time for reversal of motion of moving member springing the arc and complete interruption.

This type of oil circuit breaker is of the 10-break or multiple-break type. It is of the comparatively slow-speed design. In no case was the speed of the moving element higher than 2.8 ft. per sec.

The statement is made that records have been taken on 110-kv-a. oil circuit breakers both on 2-break and 6-break types, with speeds varying from 4 ft. per sec. to 15 ft. per sec. per contact and a range of arcing time from 12 cycles on the slow speed to 2 cycles on a higher speed. This would infer that the higher-speed breakers clear the arc more quickly than the slower-speed.

It is also stated that "the important point often overlooked is that the high-speed breaker clears the disturbance in much less time with much less damage both to system and to the breaker."

Records are available showing the type BO-60, 110-D, American Brown Boveri Electric Corporation oil circuit breaker, performing on O-C-O cycle with short circuit in the order of 500,000 kv-a. wherein it is shown that very slow speeds will interrupt the arc in the same time of arcing as with higher speeds. It was shown on one test that the average speed was approximately 5.5 ft. per sec. on opening and on the second O-C-O of the operating duty the speed was reduced to approximately 1.4 ft. per sec., approximately 50 per cent of normal, yet the time of arcing remained the same.

It is our belief that, contrary to the general thought, the introducing of greater speeds alone does not necessarily give better oil-circuit-breaker operation. It is our belief that the use of the 10-break multiple break with slow moving mechanical parts presents many advantages. Due to slow speeds there is no racking of mechanism at the end of the stroke, whether on closing or opening,—only simple torsional accelerating springs are used. There is no quick-break mechanism of any kind, hence no triggers, latches, nor springs.

Furthermore, it has also been demonstrated on tests that close to 700,000 kv-a. the use of the 10-break breaker gives pressures less than 20 lb. per sq. in. in the tank.

There have been some misconceptions as to the length of arc per arc and the total arc length in breakers of the 10-break type. It is true that if the speed of the moving element were the same in the 10-break type as in the usual 2-break type the total length of arc in the 10-break type might exceed that of the 2-break type. However, the speed of the BC-60 American Brown Boveri high-voltage oil circuit breaker is comparatively low, so that the total length of arc is very little if any greater than would be experienced on a 2-break type under the same conditions. It is definite that the length per arc is much less in each of the 10 arcs than the length of each arc in a 2-break type.

The paper makes a reference to the use of resistance in conjunction with one multiple-break oil circuit breaker. Reliable resistance-type multiple-break oil circuit breakers have been built in Europe for many years. Resistance is mounted within the tank at a point such as to clear it from precipitating carbon and low-dielectric oil at the bottom of the tank. The usual method is to connect resistance in shunt with 4 or 6 of the multiple breaks, leaving from 2 to 4 of the multiple breaks in series. Upon interruption the arcs which are shunted by the resistance are immediately made unstable, thereby leaving very high resistance in series with 2 to 4 arcs. This gives a high resistance against the recovering voltage, cuts down the current flow and acts to diminish the time of arcing. Breakers of the 110,000-volt class with interrupting rating of 500,000 kv-a. of the resistance type have been built and successfully operated for a number of years.

In summarizing we would point out that the high-voltage oil circuit breaker as manufactured by this corporation will probably come nearer meeting No. 1 requirement on the eighth page of the paper than any others on the market today. This requirement is that the complete O-C-O cycle shall not be more than 0.20 seconds. Interrupting-capacity tests in the order of 500,000 kv-a. show a time of 0.22 sec. average. The operating mechanism for these breakers is of the motor type, simple in construction and requiring very small current for operation. The power demand is less than 1 kw.

The breakers are of very simple construction, such as will enable them to go through many operating cycles with very little inspection.

Philip Sporn: (by letter) I am pleased that the authors have tackled a question that has not been given the attention it deserved, and that is the question of oil circuit breakers and their effect on continuity of service in transmission networks.

I think some work ought to be done also with particular reference to the effect on continuity of service of switching arrangements on high-voltage lines.

As a general rule a transmission line is planned and built by the transmission engineering department and when it is all over the job is given to the relay engineer to relay it. Sometimes he actually knows something about it a few months in advance of completion but it is very seldom he has much of a say in the arrangement of the line and the effect it will have on his various loop circuits. The fact that this additional line will make selective action almost impossible or, if it does make it possible, will introduce unusually high time settings on some of the lines, is not given very much weight and the problem is generally considered one of minor importance and one that a good relay engineer ought to be able to take care of. Of course where a double-circuit line between two points is involved, the problem is very very simple but very often the double-circuit lines do not materialize or where a line is laid out for two circuits, a single circuit only is installed and such a period may last for five years. The introduction of a pilot system of protection on transmission lines will materially ease the whole problem of sectionalization. It will particularly make possible the reduction in the time a fault is allowed to stay on the system and this will reduce to a negligible quantity not only the damage done during a fault but will also improve stability and will further reduce the trouble on customers' apparatus as a result of long surges on transmission systems.

Obviously if a carrier-current pilot system of protection is to be effective it has got to have a reliable means of coupling and Mr. Belt has shown[1] some of the devices that can be and are being employed today to obtain reliable and effective coupling. It is of course evident that there is no sense in making large expenditures on a relay system such as a carrier-current pilot system that will cut down relay action on a single line from 2 or 3 sec. to ½ sec. if the breaker itself will take an equal amount of time to function in clearing a short circuit after the relay system has energized its trip circuit and this point has been brought out very well by Messrs. Wilkins and Crellin. As an example of this, refer to Fig. 10 where one of the phases of a breaker is shown taking about 0.27 sec. before opening. Now, compared to a relay action of 3 sec. 0.27 seconds is quite good but when dealing with orders of time of relay action of about 0.5 sec. 0.27 isn't quite so good.

With some of the conclusions of the authors as to the fundamental requirements of a circuit breaker, I agree; with others I differ quite radically. For example, I believe that the operating time for a complete "Open-Close-Open" cycle of operations can be materially raised above 0.2 sec. provided the opening time can be reduced say to a figure approaching 0.05 sec., or, as an outside figure 0.1 sec. There is no question that the ideal half-cycle of arcing time would be a highly desirable thing if it could ever be obtained but I cannot quite see why it is necessary to limit the power demand of the mechanism to 1 kw. I do not see that it is necessary to have the breaker designed so that it can be installed, adjusted, and maintained by the average mechanic without oil-circuit-breaker technique. I should like to see them designed so that they can be installed, maintained, and adjusted and then stay put when worked on by the average mechanic who had some special training.

That it is highly desirable that a breaker shall be capable of completing more than two normal operating cycles before any inspections or adjustments are necessary, there is no room for argument. The wonder is that the present operating cycle was agreed upon and not rejected as utterly absurd by the operating people. I do not know whether 100 is at all essential but it ought to be of that order. For the present 40 or 50 would be good enough and I believe that if the operating engineers insist on it they will get it some day.

Again I am in entire agreement with the authors in that the only way for an operating company to know today as to whether the breakers that it is buying or that it contemplates buying will or will not perform satisfactorily, on its system, is to test them. Some day breaker development will have reached the point where this will not be necessary but it does seem necessary today. That this happy stage will arrive by combining all of the good features now available in the designs of the several manufacturers as the authors so confidently expect, I am not at all certain; we have seen in other lines of endeavor developments involving combinations of the best feature of each that gave a rather queer result. The problem would seem to be rather to have each manufacturer develop his design or new designs to a point where he is certain and doesn't merely think that the breaker will do what he says it will do.

R. J. C. Wood: One of the oscillograms shows the current increasing on interrupting the charging current on the line. Mr. Crellin said this was contrary to the ordinary conduct of current on short circuit.

In testing Mr. Sorensen's vacuum switch, which was done by bringing a synchronous condenser up to speed on the system, disconnecting from the system, and throwing it on the switch and using it as generator, we had occasion to notice the shape of the short-circuit current during the time previous to the opening of the switch. Quite a number of oscillograms of short-circuit current were made, some of them showing the ordinary asymmetrical type but quite as many showed the short-circuit current increasing for the first few cycles.

E. A. Crellin: It was short-circuit current.

R. J. C. Wood: But a single-phase ground.

F. C. Lindvall: The authors mention the possibilities of the vacuum switch. We at the California Institute of Technology who have worked on the problem of breaking currents in vacua are quite gratified by this recognition, for not all operating engineers and oil-switch designers are convinced that some day the vacuum switch may be a reliable piece of station equipment.

We feel that our optimism regarding the switch is justified, and that the fundamental idea of the switch is sound. Yet, as Mr. Crellin pointed out, the transition from a rather delicate piece of laboratory equipment to a reliable device for commercial service is a long step which presents numerous difficult technical problems; but fortunately, as more new work is done on the switch, many anticipated difficulties eliminate themselves.

Two such points that the authors mentioned in their paper should be discussed briefly. First, we have found that the extremely high vacuum which was originally assumed to be an obvious prerequisite is not really necessary. This interesting fact was observed in a general way in the earlier vacuum switches, but in order to obtain more definite data on this point a small switch was constructed. This model had butt contacts of ½-in. aluminum rod. An ionization gage located between the switch and the cut-off from the diffusion pumps served for measurement of gas pressure in the switch.

For convenience in testing, the duty cycle of this model consisted of short circuiting and immediately opening the short-circuit on the high side of a 15,000/220-volt 10-kv-a. transformer. The short-circuit current through the switch was 3.5 amperes and the potential across the switch after break was of course 15,000 volts. For the first 20 or 25 trials of the switch at a pressure of 2×10^{-5} mm. of mercury severe arcing resulted with consequent liberation of gas from the electrodes. However, the contacts were then in shape for proper switching and successful operation followed. In fact, at a vacuum of the order mentioned, an arc could not be drawn out to maintain between the contacts even with maliciously slow operation.

Several runs of 400 or 500 operations were made with the switch cut off the pumps with careful note taken of time and of

1. *Coupling Capacitors for Carrier-Current Communication*, T. A. E. Belt, A. I. E. E. JOURNAL, October, 1927, p. 1051.

changes in the vacuum. These pressure changes were then compared with leakage curves taken on the switch, and the interesting result was that the rise in gas pressure during the long switching runs followed very closely the curves of leakage coming from a faulty seal. In other words, the amount of gas given out by switching with clean electrodes was but little.

The switch functioned consistently and was apparently indifferent to existing gas pressures up to the order of 5×10^{-3} mm. Beginning at somewhat lower pressures decided flashing could be seen at each operation of the switch, but every time a successful break was made. As a matter of fact, the switch would break current satisfactorily with sufficient gas present to give a solid negative glow from a spark coil through a side discharge tube. Hence, to generalize from these results it follows that with outgassed contacts only a tolerably good vacuum, one which is relatively easy to get and easy to maintain, is needed for successful switching. Thus, at once, many of the troublesome details of high-vacuum technic are avoided, and in consequence the switch lends itself more readily to the ordinary methods of manufacture.

The second point mentioned by Mr. Wilkins and Mr. Crellin, that of operating the contacts within the vacuum chamber, has been simply and adequately solved through the use of flexible bellows, which makes possible moving the switch contacts through any required distance by any suitable mechanism. As a consequence the switch may be locked in closed or open position, a feature demanded by the operating engineer.

We have also found that extreme speed of opening is unnecessary in the vacuum type of breaker. Thus the contacts themselves may be simple and have low inertia. In turn, the operating mechanism may be of light construction, permitting the operating speed of the switch as a whole to be made extremely high. This speed, together with the characteristic first half-cycle break of current, will give a circuit breaker whose operation will no doubt be rapid enough to meet modern switching requirements.

A further desirable feature would follow in that the simplicity of the operating mechanism of a vacuum switch should allow an accuracy of adjustment which would result in more nearly approximating the simultaneous breaking of current in the three phases of the switch.

R. W. Sorensen: Reference has been made to the development of gas pressure tending to rupture switch tanks when a switch is open, and the question has been asked, does this phenomenon of pressure occur in the experimental vacuum switches when such switches fail to function properly and do not interrupt the current? It would be natural to expect in case of failure to interrupt the circuit that gases might be given off from the switch terminals in sufficient quantity to develop pressures that would cause an explosion or bursting of the chamber containing the vacuum switch. Experiments which have been made with the vacuum switch in which over 150,000 kv-a., single-phase has been interrupted by means of single-pole switches have failed to show enough gas pressure to produce explosion. Also, when circuits of this capacity have not been completely interrupted by the opening of the switch, the switch has withstood any tendency toward an explosion. In a few cases where the glass container for the vacuum chamber has broken, whether due to heat or mechanical injury, the parts of the glass container have not been thrown about so as to indicate an explosion, but have rather simply dropped to the ground and done no damage; in fact, we have had less flying of glass than is often the case when an ordinary electric light globe is broken. As an indication of our confidence that no explosions occur, I may say that those of us who are working with switching in vacuum have so little fear of flying glass or other parts that we stand within a few feet of the switch in order to watch its operation when experiments are being conducted; in fact, we approach the switch much closer than has been considered safe with oil switches which may throw oil.

Another very favorable feature of the vacuum switch is the low voltage rise in the circuit at the time of break. For, though the vacuum switch always breaks the circuit on the first half cycle, we have found the voltage rise with the vacuum switch to be less than with the oil switch. The oil switches we have worked with usually hold the arc 8 or 10 half cycles. That is, there seems to be more rise in voltage on the circuit at interruption when it takes several cycles to make the interruption than there is when interruption is made during the first half cycle. Many times in our laboratory we have put one of our vacuum switches in a convenient 15,000-volt circuit capable of supplying current up to 150 amperes and have, by means of the hand-operating lever, opened and closed the switch rapidly, perhaps six or eight times per second. This we can do 25 or 30 times without distressing the switch in any way. I have never seen such a demonstration made with an oil switch. In fact, the amount of energy expended in the switch does not seem to be great, the actual drop across the arc at separation of contacts being probably less than 100 volts. This means that there is not available a great deal of energy at the place where it will destroy switch contacts. One of our small switches, the contacts for which are rods 3/8 in. in diameter, has been used to open a 15,000-volt circuit, the current in which varies from a small amount to 125 amperes, more than 4000 times and the contacts show no appreciable pitting. I feel that we may safely say, therefore, that a vacuum switch which has been properly tuned up for operation will give good service and be able to interrupt circuits almost an infinite number of times without damage to contacts.

I do not wish in any way to give an impression that vacuum switches are ready for the market. During the five years we have been working on the switch we seem to have made small progress. Each move, however, has been a progressive one and perhaps it will not take five years more to develop a switch which will have some degree of success in practical service on power lines.

In conclusion, I can reply to Messrs. Wilkins and Crellin by saying that we have developed a means for moving practical circuits in a satisfactory way. We have also been able in an experimental way to fulfil requirements 1, 2, 3, and 4 as listed in their paper. Requirement No. 5 is the one we have not as yet been able to meet.

E. K. Sadler: We have just completed some over-all tests, at our factory, which approach Messrs. Wilkins and Crellin's specifications; and I should like to make a few remarks on that.

We have found it possible to obtain the following speeds without complicating the operating mechanism or subjecting the switch to excessive jar in operation. This switch was of the six-break type and the speeds given are the total for all six breaks.

We have obtained a velocity of 51 ft. per sec. when the arcing contacts break and a maximum velocity of 75 ft. per sec. at a point some inches beyond where arcing contacts break. Opening of switch requires only 0.089 sec. for full travel of blades, and an elapsed time of 0.16 sec. from energizing the trip circuit until the arcing contacts open. The total break equals 36 in.

As regards a switch jumping when the operating mechanism is mounted remote from the switch; this switch can move 2 in., back, forward, right, left, up or down and still operate perfectly.

J. P. Jollyman: From the standpoint of the engineer having to do with the operation of a power system, we are very much concerned with the effects of trouble on the power system. We want to get those troubles off the system as quickly as possible. We do not want to wait until the voltage of the system is reduced to a point where the duty on the circuit breaker is reduced. We want the trouble removed before service is impaired and whatever kind of switch it is will have to stand this quick service.

J. S. Thompson: (communicated after adjournment) It is of incalculable value to the manufacturer of oil circuit breakers to secure the findings of engineers who have so thoroughly studied the problems to be met in oil-circuit-breaker design and to have the result of these studies summarized in the requirements which they have laid down.. These requirements are looked upon as supplementary to most of those outlined by Mr. Jenks of the West Penn Power Company, in the paper appearing in the 1924 TRANSACTIONS of the A. I. E. E., p. 648.

With reference to requirement 3, it is possible that a statement that the mechanism should demand but a very small amount of power would be sufficient, but the exact reference to 1 kw. is presumably prompted by the fact that mechanisms are available which require no more power than 1 kw.

With regard to the discussion presented by Mr. Sporn, it would appear that his reference to the absurdity of the test duty cycle demand is based upon a tendency to look upon test rating as synonymous with normal operating ratings in circuit-breaker practise. In all other apparatus the test ratings to which the apparatus is submitted, for periods such as one minute, are far in excess of the operating rating and therefore it is possible that some adjustment should be made so that the circuit breaker operating twice under the A. I. E. E. test rating would operate comfortably at a reduced operating rating for the 100 or even the 1000 operating cycles referred to in requirement No. 4. We would draw attention to the fact that the N. E. M. A. rule for reduced interrupting capacities, under item E, suggests the ratio which these two ratings might bear to each other.

With regard to the discussion presented by Mr. Hilliard, the uncertainty regarding circuit breakers on the part of those best informed is indicated by the phrases: "It is quite likely"; "Not half"; "One may expect"; "It is probable"; "Could undoubtedly"; "May result"; "Is likely to be"; "It is not impossible."

Mr. Hilliard appears to assume that doubling the speed of the break would invariably double the length of the arc, and with respect to this assumption, we would draw attention to Figs. 4 and 10, showing arc durations of two-break and six-break circuit breakers under exactly similar conditions. These curves indicate a duration of arc of 0.045 sec. in the six-break circuit breaker and 0.15 sec. in the two-break circuit breaker.

There would appear to be an inconsistency in Mr. Hilliard's reasoning where he suggests that a greater quantity of gas is developed by high contact speed, whereas later in his discussion he states that high speeds are advantageous.

Mr. Hilliard indicates that high-speed interruption produces voltage surges and also impact pressures in the oil. If this is the case it would appear that voltage surges are a necessary concomitant of high-speed circuit interruption. But regarding tank pressure, it may be stated in support of multiple breaks that no Pacific Electric Manufacturing Company six-break oil circuit breaker tank or top casting has ever been damaged either under test or operating conditions, nor have tank and cover assemblies ever been forced apart.

Mr. Hilliard makes the point that the long break is of value and, recognizing this, the Pacific Electric Manufacturing Company provides that each one of the six breaks of its circuit breakers is substantially as long as each one of the breaks of the conventional two-break oil circuit breaker. Properly disposed multiple breaks can be considered as a grouping of two-break oil circuit breakers in series, and could not be assumed to draw arcs, per pair of breaks, as long as a single two-break oil circuit breaker. This fact has been put in practical application on a Pacific Coast operating system on which the failure of a two-break circuit breaker was remedied by placing a similar two-break circuit breaker in series with it, the two mechanically connected to operate simultaneously. But a further advantage of six-break circuit breakers is obtained by so disposing the breaks that the explosive effect of one arc tends to blast a volume of oil through the path of adjacent arcs.

With regard to the comment submitted by Mr. Strang, the factor of inherent time delay in the tripping mechanism is a vital one. In developing the motor-wound spring-operated mechanism devised by Mr. Wilkins, the engineers of the Pacific Electric Manufacturing Company gave this factor prime consideration, with the result that the inherent time delay in this control is satisfactorily brief. It is possible that the control referred to by Mr. Strang could be corrected to secure equally excellent characteristics.

E. A. Crellin: Everybody seems to have remarked about the power demand of the operator being limited to one kw. Mr. Samuel says, "Give me a good breaker and I do not care if it takes five kw. to close it." It is granted that it makes little difference to the switch itself how much power it takes to operate it so long as there is sufficient to get the contacts in or out in fast time. The limitation was added for another purpose and was included along with the other specifications to complete the list of requirements.

Let me point out what is involved in a large operator power requirement, especially in a breaker which requires practically the same energy to open as to close. I recently visited a substation in which there will ultimately be some fifty 60-kv. breakers and six or eight 220-kv. breakers, the most remote of which are 900 or 1000 ft. from the switchboard. If it is necessary to have operating currents on the order of 200 amperes at 125 volts, we are faced with a very great expense in storage batteries and control cables in order to hold up the operating voltage. It may well happen that a group of breakers will be simultaneously tripped, and if they require heavy operating currents to open, will force the installation of expensive equipment. Even with the gravity-opened breakers, it may well be that a large series of successive operations will lower the battery voltage to a point where further operation is impossible. The reason for imposing the limitation on operating power was to effect economies in installation. Such operators are available, and greatly to be preferred to those requiring 200 or more amperes.

Mr. Williams and Mr. Strang both have the same thought on the definition of speed. It is high over-all speed until the circuit is cleared that we are after. If the actual time of contact movement is kept relatively high for reasons of switch design, then speed must be attained in the operating mechanism in order to bring down the total time from the closing of the relay contacts to the final interruption of the circuit. In this paper "speed" does not mean the rapid motion of parts so much as it does the rapid interruption of the circuit, no matter how attained. It is felt by the authors, however, that much higher contact speeds than those at present obtaining will be of great advantage not only in preserving system stability, but in easing the stresses within the breaker itself.

Roy Wilkins: Mr. Hilliard states that "for years it has been known that speed was one of the chief factors of an efficient oil circuit breaker." Nothing seems to have been done about it, however, until very lately.

With regard to the testing of breakers below their rating, it might be well to point out that most of the failures on operating tests including those at Canton have been very much below the breaker ratings.

Mention was made of the fact that substantially instantaneous interruption causes very great voltage rises. This was the original argument against oil circuit breakers and is as true today as it was in 1895. There are as yet, however, no commercial oil circuit breakers that even approximate instantaneous interruption. No one has any hope of getting under the first half cycle. Mr. Sorensen has noted no alarming voltage rise at one-half cycle. In this connection, as was pointed out in the paper, the circuit characteristics are the determining factor on such phenomena.

With regard to guarantees, there were last year in one State of the U. S. some twenty times as many law suits for damage due to defective transformers as there were due to oil circuit breakers; the same arguments hold for both as far as care and maintenance are concerned, yet no reliable manufacturer proposes to withdraw the transformer guarantee.

With regard to the meaning of interrupting capacity in kv-a., I am frank to state that I, for one, am doubtful of what it means, if anything. Several years of intensive study in both the field and factory have so far only strengthened this doubt.

Multiplying a voltage on the bus before trouble by the current in the first one-half cycle of arc after trouble has no physical meaning and so far as yet demonstrated no practical one.

With Mr. Strang we are in thorough accord; it is a performance that is desired. The particular mechanism required may in the end not even remotely resemble any of the present types. The effect of trouble on the system is important, the effect on the breaker incidental, though all too often it is the controlling factor.

In reply to Mr. Edsall, I wish to emphasize again that what the purchaser buys is equipment to separate an operating system from a fault,—the fault and the oil circuit breaker condition at the time are secondary matters. While slow speed may be good for the breaker it decidedly is not for the system.

Breakers must be built whose opening time is under 0.1 sec. preferably as low as 0.05 sec. and whose arcing time approaches closely the optimum of ½ cycle.

Executives have been busy in the past with other matters, but of late they are giving more and more time to interconnection and network operation and the effect of combinations of networks. Eventually they will learn that the reliability of the entire network depends on the ability of the circuit-interrupting equipment to function properly in less than the time required for the parts of the network to pull out of synchronism and such circuit-interrupting equipment will then be demanded and made.

The point and purpose of the paper is not an attempt to design an ideal circuit breaker but to outline the requirements.

There are at present two theories or methods of network operation,—one with relatively light ties in an extensive network where each load is fed from more than one source, and in trouble, the smallest practicable section is isolated. Such systems require fast relaying and insure continuous service and are represented by the Pacific Coast, the Southeastern and the North Central networks in the United States, all covering extensive territories.

The second method depends on a backbone with radiating feeders where large blocks of power are transferred from the general source to the loads and where outages are not expected on the main arteries. Such systems provide only emergency relaying on these main lines because their loss means the serious crippling of the system, and extremely fast operation would not be necessary. No such system exists today in practise on anything like the scale of the type given above.

Lightning Protection for Oil Storage Tanks and Reservoirs

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Synopsis.—This paper outlines work done in connection with planning a protection scheme for the oil storage tank farms of the General Petroleum Corporation of California. The work shows that the average annual number of storms at a given location is a constant. The dielectric property of oil has no influence in causing lightning or inducing it to strike oil in storage.

Tests show that excellent protection can be obtained by towers properly installed, but they do not indicate absolute immunity against hits.

The work done also shows that an extensive field program, supplemented by such laboratory work as required for understanding and assisting the field program, should be carried out to extend our knowledge of lightning phenomena and protection.

* * * * *

INTRODUCTION

IN California, the production of great quantities of oil has made necessary the development of storage capacity for millions of barrels of oil of varying degrees of inflammability.

Three types of storage containers have been used; all steel tanks, tanks with steel walls and roofs of some other material, and large concrete basin-like structures commonly known as reservoirs.

Previous to 1926, on California oil properties, fires resulting from lightning were scattered as to time and place. Also, insurance rates for damage to these properties by lightning were sufficiently reasonable to make such insurance more economical than the employment of protective measures for oil or oil products against induced and direct-hit ignition by lightning.

Three major fires which occurred during April 1926, resulting in the loss of several lives and almost $20,000,000 worth of property, immediately caused a large increase in insurance rates and entirely changed the aspect of the problem in emphasizing the fact that insurance can never compensate for the economic loss involved in the destruction of large quantities of oil.

The average number of thunderstorm days per year for a given geographical location is, according to Weather Bureau statistics, a constant which has not changed during the period covered by their records (Fig. 1).

In different parts of the United States, the number of such days varies from less than 5 to 95 per year. Small areas within the divisions represented by the reports may have a greater or less number of such days.

The probability of damage by lightning in any given area is largely a function of the number of storms occurring within that area, the amount of the area occupied by life and property, the character of structures or materials included therein, and the absolute humidity—which determines the percentage of lightning discharges that will occur as strokes to ground.

Each year adds to the portion of any given region occupied by life and property and increases accordingly the probability of loss of life and damage to property. For this reason, not only the petroleum industry but also other industries should consider means of protection for the future in addition to those required at present, and should make it possible for engineers and scientists to plan and execute a thorough program of field researches on the character of lightning discharges,

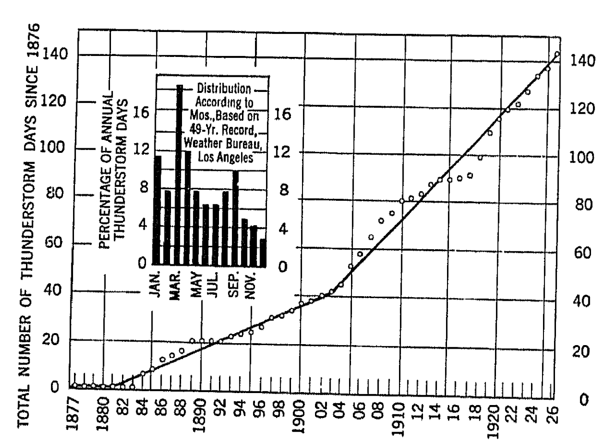

FIG. 1—NUMBER OF THUNDERSTORM DAYS IN LOS ANGELES SINCE 1876

Cumulative chart from records of the Weather Bureau. In this form a straight line indicates a constant thunderstorm frequency. It should be noted that in 1903, an alteration was made in station regulations equivalent to changing the official definition of a thunderstorm from "thunder with rain" to "thunder with or without rain." This explains the increase in thunderstorms recorded since 1903. (From Marion E. Dice, "Lightning Hazards," *Oil Bulletin*, 13, 27, Jan. 1927.)

supplemented by such laboratory work as may be required for the development of the apparatus for these tests and interpretation of the results obtained in the field.

Directly following the 1926 oil fires, several oil companies using the laboratories at the California Institute of Technology as a base, independently or in cooperation with members of the Institute staff, undertook the problem of designing protection for their oil storage properties. The most extensive of these programs was conducted for the General Petroleum Corporation by Marion E. Dice of their Consulting Engineer's Depart-

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ment and the California Institute of Technology High-Voltage Laboratory staff. It forms the basis of this paper.

Effect of Location on Lightning Hazard

Given a geographical section within which certain industrial operations are to be carried on, are there spots within that area which vary as to the probability of a lightning discharge?

A study of contributing causes for lightning, such as the breaking of water drops in upward currents of air[1] at the required velocity, showed that much can be done in reducing the lightning hazard by proper location with respect to thunderstorm paths.

Lightning damage may be caused by direct stroke or by ignition from secondary or induced discharges. As the energy in discharges caused by induced charges is relatively small, oil fires from this means can result only by such discharge acting as ignition systems. The obvious method for guarding against such effects is to reduce to a minimum the storage of highly combustible oils or gases given off by oils, and to keep well guarded against spark discharges the oils that are the more highly inflammable or give off gases which, with air, form explosive mixtures.

The well-known impossibility of producing differences of potential between two objects within a completely closed conducting envelope by influences exerted without the envelope indicates the proper solution for the problem of induced discharges. In practise, therefore, the desired protection from induced effects has been obtained by storing readily inflammable oils or oils which will give off explosive gases in all metal tanks, with well screened and properly designed vents or by the use of wire networks over wooden roofs. Floating roof construction, which reduces to a minimum the free gas space above oil in a tank, is an aid to this form of conservation. Tanks constructed in this way are costly and it is therefore not practicable to use them as general storage for the millions of barrels of oil now stored. Fortunately a great percentage of the oil can be reduced to a heavy residuum of low volatility for storage. This heavy residuum can be safely stored in the large reinforced concrete reservoirs, used so extensively in California, or in metal tanks with non-metal, non-floating roofing, providing such reservoirs or tanks are protected from direct hits.

Before discussing methods of guarding against direct hits, the authors wish to present some data bearing upon the possibility of any special phenomena related to lightning which may be directly chargeable to the influence of the oil itself.

Collection of Charges on Oil Surfaces

It was suspected at one time that certain oil fires of unaccountable origin might have been due to ignition from sparks caused by independent charges accumulating on parts of a large oil surface and then coming near enough to each other to have their charges equalized by a spark between them. The apparatus shown in Fig. 2 was used to make tests relating to this possibility. With voltage applied to the pan and terminal above it as electrodes, charges could be detected at the surface of the oil only while such voltage was applied. Also, during the application of voltage, the oil was always in circulation, the rapidity of circulation being a function of the potential gradient through the oil. Bits of cork or other insulating material in the oil would show a rather definite circulation path from the strong field under the rod above the pan out to the weaker field. Frequently particles of insulation material in the oil, because of some pecularity of shape or color, could be singled out and watched. Many of these particles were seen to act as though they were in the business of carrying charges from the surface of the oil to the pan at the bottom; that is, with a rate of motion entirely apart from the rate of circulation of oil, these particles would come to the oil surface, move down until they touched the pan at the bottom, and then come to the surface again to repeat the operation. As a further check, a charged electroscope was con-

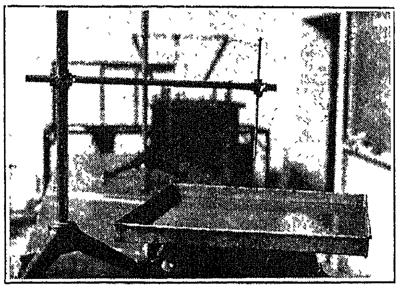


Fig. 2

nected to a conductor which was allowed to touch the surface of the oil. In every case the electroscope was very quickly discharged. Also, it was found that the electroscope could not be charged above the potential drop through the oil so long as it was kept connected to the surface of the oil. These tests showed, as did similar earlier[2] ones, that oil cannot accumulate charges at points on its surface. Thus, there need be no fear of isolated or local charges on the surface of oil building up or approaching each other, and igniting the gas above the oil by spark discharges.

Influence of Oil on Spark Discharge

In planning protection for oil storage, one is confronted with the question; does oil have to be considered as a special problem because of characteristics which have influence, different from those of other substances, in directing the path of a lightning discharge between a charged cloud and the earth, or because of

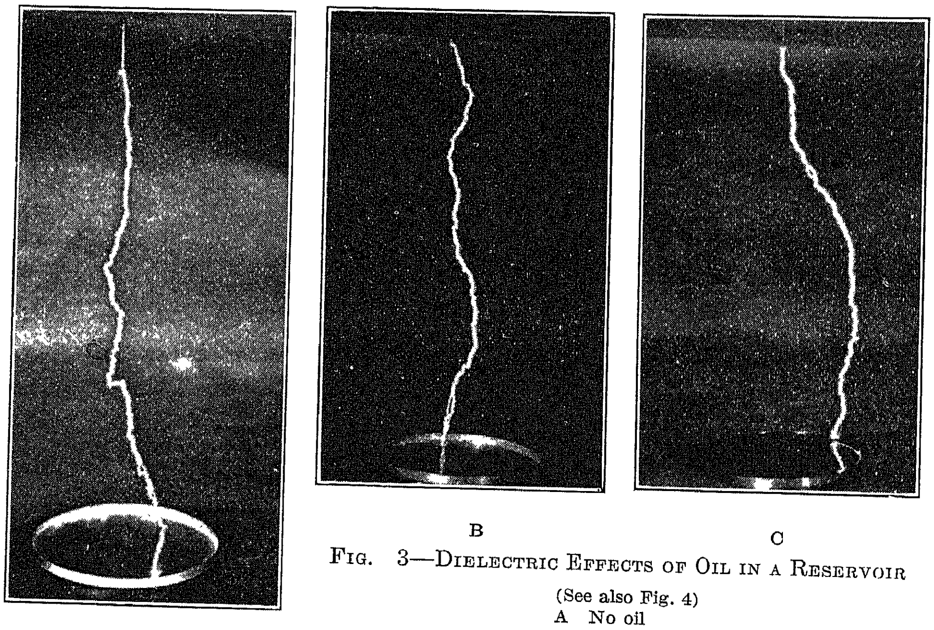
1. For all references see Bibliography.

2. Loc. cit.

any special phenomena relating to the accumulation of charges on the surface of a body of oil.

It is a known fact that when a high potential direct current is applied to two electrodes insulated from each other, a dielectric, such as glass or mica, placed near the positive one, materially lowers the voltage required to give arc-over between the two terminals.[3] At the suggestion of E. R. Wolcott of the Union Oil Company of California, oil, being a dielectric, was examined for such an effect with negative results. There was found no evidence that spark-over voltage between two charged electrodes was changed by placing oil on the positive one. This is fortunate, for if oil in a reservoir on the ground could act to lower the discharge voltages, there would be a great hazard for the oil, whenever a negative cloud formed in the region of storage.

This absence of any influence of the oil to cause it to be a more probable target for spark discharges was also checked by the use of the piece of apparatus shown in Fig. 2. This apparatus consisted simply of a large shallow pan partly filled with oil. With an electrode above the pan (as shown), connected to one terminal of the source of direct current supply and the pan connected to the other many tests were made. These tests show that as the voltage was increased, the oil was agitated more and more violently until, as the voltage approached that required for arc-over, the oil was hollowed out under the upper electrode, as though blown away, and when the depth of oil directly under the electrode was sufficiently small, the arc struck through the oil to the pan. If the voltage was kept constant and the oil level in the pan raised by adding more oil, the depth of oil (or, in other words, the thickness of insulation over the pan), was increased, and no arc from upper electrode to pan took place. Also, when the oil film was not punctured, there was no arc discharge from the upper electrode, the discharge around this electrode being limited to the corona discharge; that is, an arc does not strike from a conductor to an insulator unless the potential gradient over the insulator is great enough to either puncture the insulator or carry the arc around it through the medium surrounding the insulator. This is a fact of which one sometimes loses sight in thinking of the action of two insulators having different dielectric constants when placed in series in an electric field. When voltage is applied to such an arrangement, while it is true that the greater stress is upon the insulator with the smaller dielectric constant, it is also true that in order to obtain an arc there must be complete breakdown of both dielectrics by puncture or arc-over, as the arc cannot strike through one dielectric to the other as a terminal.



A B C

Fig. 3—Dielectric Effects of Oil in a Reservoir

(See also Fig. 4)
A No oil
B No oil
C Oil in reservoir

As a further check upon the inability of oil in a vessel to cause the discharge to take place more readily, many tests were made with smaller pans, dimensions of which were proportional to those of reservoirs. These were placed on the floor below the electrode used to represent a cloud, the other terminal of the power supply being grounded to the floor. With oil in the pan, the discharges missed the pan altogether or struck the edge; without oil in the pan, the discharges would hit in the pan or at the edge indiscriminately as shown by Figs. 3 and 4.

Lightning Strokes

There are three possible ways of guarding against direct hits; *viz.*, to prevent the occurrence of lightning discharges between clouds and earth, to construct

3. Loc. cit.

the tanks or reservoirs in such a way as to provide immunity to damage from such hits, or to direct the hits elsewhere to conductors which will harmlessly carry a discharge occurring between cloud and earth until all energy of the discharge is dissipated. All of these suggested solutions were discussed shortly after Franklin's invention of the lightning rod in 1752, were revived and again thrashed out about 100 years later when Sir W. Snow Harris devised lightning conductors for ships of the English Navy, and more than 50 years since were reduced to scientific analysis by Sir Oliver Lodge.

To prevent lightning discharges between clouds and earth, it is necessary to provide a means of preventing the accumulation of sufficient charge on cloud and earth to

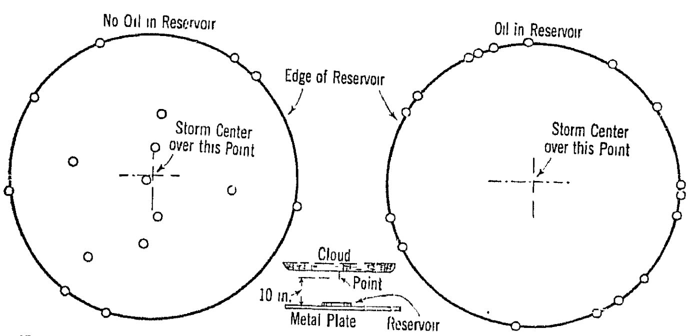


FIG. 4—DIELECTRIC EFFECT OF OIL IN A RESERVOIR WITH GROUNDED WALLS

These records show that the presence of oil in a reinforced concrete or metal reservoir tends to direct electrical discharges, which would otherwise strike into the body of the reservoir, to the edge. At the same time, the presence of a body of oil of the proportions of a reservoir in a thunderstorm field does not affect the number of discharges which fall within that area. Oil does not attract or repel lightning. In the tests, discharges from the surge generator were directed into a scale model of one of the 500,000-bbl. Wilmington reservoirs when empty and when full of oil (13 deg. residuum). The storm center was over the center of the reservoir at an elevation of 1000-ft. (actually 10-in.). The small circles show the location of hits.

Results

Point Struck	Reservoir Empty	Reservoir full of Oil
Edge..........	8	17
Inside.........	8	0
Outside........	4	3
	20	20

cause a discharge to take place between them. There are no known records of this having been accomplished in such a way as to make available any data on energy discharge from structures erected for this purpose, though there have been many schemes suggested[4]. These schemes rely for the most part upon the use of points attached to earth as a means of discharging the charges produced. Tests to determine the value of such a scheme should be made on actual tower and point installations in a district subject to many lightning storms. Not having available such an equipment, tests were made with laboratory apparatus as shown in Fig. 5. This apparatus was constructed to scale and tests made for several conditions involving different actual dimensions.

In these laboratory tests, steady unidirectional fields were used, because, had alternating fields been used, the total current measured would be the resultant of an energy current in phase with the voltage and the charging current leading the voltage 90 degrees. Lack of a proper wattmeter for use under such small current,

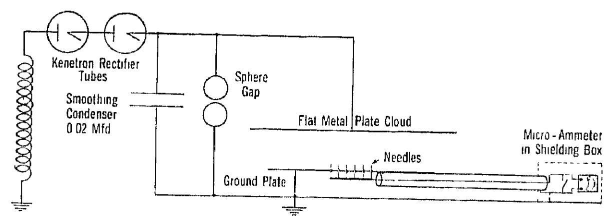


FIG. 5—DIAGRAM OF TESTS ON DISSIPATION OF ELECTRIC CHARGE BY NEEDLE POINTS

high-voltage conditions would make the separation of these components very difficult. There are also other difficulties with alternating fields, such as distorted waves having greater peak value on the positive half cycle than on the negative half cycle, which make the separation of energy current from total current practically impossible. With direct current, these complications are avoided and the conduction current between points and the upper plate has a steady value for any given voltage.

The apparatus (Fig. 5) consisted of two parallel flat metal plates, mounted horizontally and insulated from each other. The upper plate represented the thunder cloud and by means of the kenotron and condenser equipment shown in the figure, could be charged to a maximum potential of 100 kv. The lower plate was connected to ground and represented the earth surface under the thunder cloud. A number of steel needles,

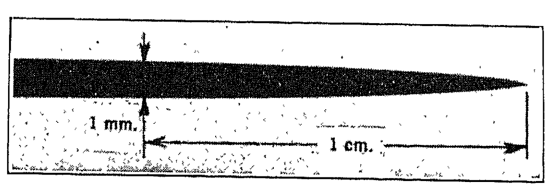


FIG. 6—DIMENSIONS OF NEEDLES USED IN FIG. 5

(Fig. 6), projected through holes in the grounded plate. Each needle was insulated from the plate by means of a small piece of glass tubing and all the needles were connected together at their lower ends by a third, smaller, flat metal plate which in turn was connected to ground through a micro-ammeter. The connecting lead was carefully shielded against induced charges by a grounded metal tube which surrounded it, and the micro-ammeter itself was placed inside a grounded screen wire cage.

For each set of readings, the upper plate was set at a

4. Loc. cit.

given distance above the lower one, the points were raised above this plate 1/12 the distance between plates, and the needles were separated a distance of four times the needle height. The sphere-gap was set for a desired value and voltage was applied, slowly increasing until the gap sparked over, at which time the micro-ammeter was read.

Results of some of the tests made are shown in Fig. 7. Each curve demonstrates the relation between the average voltage gradient between the plates and the conduction current from the points. The curves give no constant relation between conduction current and gradient, but indicate so many variables as to make it impossible to draw many conclusions from the data at present available.

On the other hand, the curves show that the conduction current is practically zero (less than 10^{-8} amperes) up to a certain critical gradient in each case. From this point, as the gradient is increased, points are obtained according to some regular law (which permits them to be plotted as points in a curve). They also show that the current is influenced by the actual size of the apparatus within the range available in the laboratory at the present time, but it is inconceivable that the same order of increase of current with increase of scale will be maintained up to the scale of clouds and lightning towers in actual use.

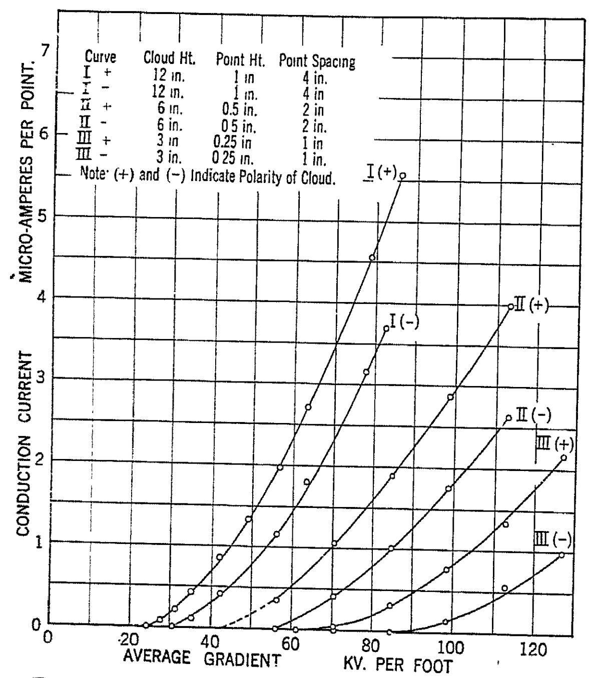


FIG. 7—DISSIPATION CURRENTS OF NEEDLE POINTS DISCHARGING AN ARTIFICIAL CLOUD

If conduction current great enough could be obtained, there would be a possibility of keeping the potential between earth and clouds down to a value too low for the discharge by lightning. Some calculations based on the data obtained from the tests just described, and from other investigations, may be of interest in this connection.

C. T. R. Wilson[5] shows that a probable charge of 50 coulombs is neutralized by a lightning flash. Simpson[6] states the total charge to be of the order of 100 coulombs. Norinder[7] found the time required for building up charges preceding lightning flashes to vary between large limits, the short intervals being only about three or four seconds and the longer ones, several minutes. Apparently a large number of them are built up in 10 sec. or less. Assuming for our calculations, a time of 10 sec. allowed for the accumulation of a charge of 50 coulombs, resulting in a gradient of 100 kv. per ft., if it is assumed that the gradient builds up at a uniform rate during 10 sec. of applied voltage the average current would be approximately 2.5 micro-amperes flowing for eight seconds, if it takes a gradient of 20 kv. per ft. to start the current as shown by Curve *I* (+), Fig. 7. The number of points required to give out this conduction current would be

$$\frac{50}{8 \times 2.5 \times 10^{-6}} = 2.5 \times 10^{6}$$

points, each of which must be 1/12 of the cloud height. For clouds 2400 ft. high, this requires 2,500,000 200-ft. towers spaced 800 ft. apart. Conceding these calculations to be largely in error, there is, nevertheless, little indication that lightning may be prevented by conduction currents from points. For cases of more rapid charge accumulation, the number of towers required would be correspondingly greater.

TANKS

The use of tanks for oils which are dangerously inflammable has been discussed in relation to induced discharges. These same tanks made entirely of metal can be made to furnish, unaided except by good grounds, protection to contents for direct hits. They need no further discussion.

LIGHTNING RODS

Franklin when he gave instructions that conductors used for lightning rods should terminate at the upper extremity, with one or more points, and extend downward until they met permanently moist earth possessed of good powers of electric conduction showed knowledge of the fundamentals of lightning rod protection far beyond that of his associates. These fundamentals are, however, insufficient for the whole solution of the problem, and must be supplemented by knowledge of lightning phenomena developed since the time of Franklin, such as was reported by Sir Oliver Lodge[8] and added to by the engineers and physicists of today.

In fact, with all our knowledge of these phenomena, such as side flashes, back strokes, electrical inertia, and the effect of location, ground conditions, etc., there

5, 6, 7. Loc. cit.
8. Loc. cit.

seem to be no general rules which can be applied to all places to be protected, and these rules are sufficiently comprehensive to make unnecessary a special study of practically each location for which protection is desired.

For oil in storage, it seems best to have the rods take the form of high towers, placed as far from the reservoirs and as far apart as practical, being at the same time near enough to each other to make almost impossible any hits to objects between them. Each tower so erected should be grounded at its base to the water plane below the tower, to all piping around the base of the tower, and to the reservoirs for which protection is being provided.

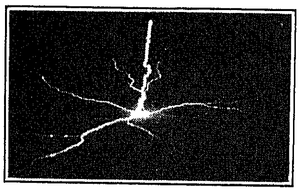


FIG. 8—SPREAD OF DISCHARGE CURRENT OVER A CONCRETE FLOOR

To avoid so far as practical, any danger from side flashes which might ignite the oil, the towers are erected at some distance from the reservoir they are to protect. Good grounds directly under the towers also assist in reducing the possibility of side flash. Fig. 8 shows a current of electricity that appears to spatter all over the surface of a concrete floor with no special provision for good grounding when a condenser is discharged into the floor. There is no evidence of this flow of current over the floor surface when it is well grounded.

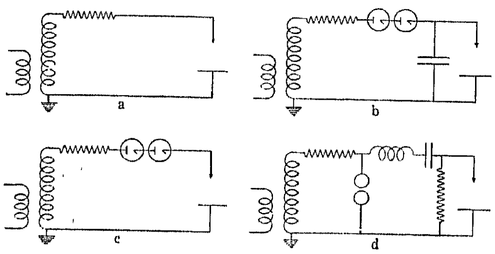


FIG. 9—DIAGRAMS OF CONNECTIONS FOR FURNISHING DISCHARGES

a A-c. 50 cycles
b D-c. with condenser
c D-c. pulsating
d Surge generator

Having decided to consider high towers, well grounded, the next step was the making of many experiments to determine the protection area about rods as single units and in groups, as set up on models in the high voltage laboratory. In making these experiments, many tests were made with a-c., 50-cycle sparks, d-c. sparks with and without condensers both for grounded positive and grounded negative terminals, and for discharges from a surge or lightning generator.[9] Connections used are shown in Figs. 9A, B, C, and D.

Results of the tests made for all types of discharge used show no absolute immunity for any area around a rod. The tests were made on models having the storm centers two and four rod heights off center. Considered from a statistical viewpoint, the number of hits within a circle having one rod height as a radius and with its center at the rod was practically nil, but there was an occasional hit even within this area which was not taken by the rod.

As the area under consideration is increased by considering larger boundary circles drawn about the rod,

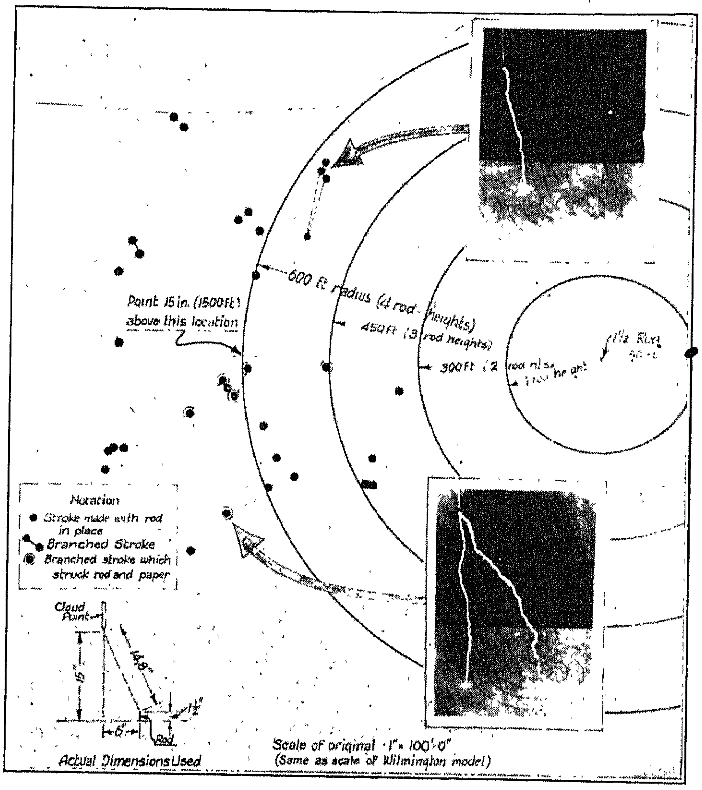


FIG. 10—DISTRIBUTION OF HITS FROM DISCHARGE NEEDLE OVER POINT FOUR ROD HEIGHTS AWAY FROM ROD AND TEN ROD HEIGHTS ABOVE SURFACE

the number of hits which can strike within a given area is increased until, at a distance of four times rod height from the rod, a circle may be drawn as indicative of the fact that beyond this point the rod furnishes little or no protection.

Results of some typical tests are shown in Fig. 10 and Tables I, II, and III. These tests show the statistical protection values for single rods for areas enclosed by circles having radii of one, two, three, and four rod heights. All tests of this type were made with apparatus set up to scale, the rod in each case being considered as 150 ft. high. The actual rods used varied in height from ¼ in. to two in., with actual sparking distances varying from about two in. to almost 27 in.

Having determined in the laboratory what one rod

9. Loc. cit.

TABLE I. PROTECTION AFFORDED BY SINGLE RODS FOR AREAS SURROUNDING THE RODS

These results are from tests made with surge-generator discharges from a point representing a cloud center located at various distances above the plane and at a horizontal distance of 4 h from the center line of the rod whose height is h, equivalent to 150 ft.
The areas in which strokes were recorded are circles of which the rod is the center and whose radii were respectively h, 2 h, 3 h, and 4 h.

Scale	Rod height	Point (cloud) height		No. of strokes with rod and without rod	Circle with radius = 4 h			Circle with radius = 3 h			Circle with radius = 2 h			Circle with radius = 1 h			Strokes to rod
					Strokes to plane within circle			Strokes to plane within circle			Strokes to plane within circle			Strokes to plane within circle			
		Actual in.	To scale, ft.		With rod	Without rod	Per cent. protection	With rod	Without rod	Per cent protection	With rod	Without rod	Per cent protection	With rod	Without rod	Per cent protection	
1 in. = 600 ft.	¼ in. = 150 ft.	$1^2/_3$	1000	50	6	35	83	2	2	0	0	0	?	0	0	?	21
		2½	1500	50	10	25	60	1	11	91	0	3	100	0	1	100	20
		$3^1/_3$	2000	50	7	16	56	4	8	50	1	3	67	0	0	?	30
		5	3000	50	7	19	63	2	11	82	0	2	100	0	0	?	15
		$6^2/_3$	4000	50	2	16	87	1	10	90	0	7	100	0	3	100	0
		8	4800	50	1	18	95	0	15	100	0	3	100	0	0	?	21
		10	6000	50	0	14	100	0	9	100	0	2	100	0	0	?	23
1 in. = 400 ft.	$^3/_8$ in. = 150ft.	2½	1000	50	12	24	50	1	9	11	0	0	?	0	0	?	15
		$3^1/_3$	1333	50	8	20	60	2	6	67	0	1	100	0	0	?	22
		5	2000	50	14	20	30	3	11	73	0	5	100	0	1	100	20
		$6^2/_3$	2667	50	8	23	65	2	14	86	1	6	83	0	1	100	9
		8	3200	50	1	19	95	1	12	92	0	7	100	0	1	100	33
		10	4000	50	2	19	89	0	14	100	0	6	100	0	2	100	26
1 in. = 300 ft.	½ in. =150 ft.	$3^1/_3$	1000	50	17	33	48	5	5	0	0	1	100	0	1	100	9
		5	1500	50	13	32	59	1	14	93	1	5	80	0	1	100	11
		$6^2/_3$	2000	50	11	19	42	4	9	56	0	6	100	0	1	100	11
		8	2400	50	4	33	88	1	19	95	0	6	100	0	2	100	33
		10	3000	50	2	12	83	1	4	75	0	2	100	0	0	?	26
1 in. =200 ft.	¾ in. =150 ft.	5	1000	50	26	27	4	4	10	60	0	0	?	0	0	?	3
		7½	1500	50	24	25	4	6	14	57	0	2	100	0	0	?	6
		10	2000	50	10	21	52	1	5	80	0	0	?	0	0	?	26
		12½	2500	50	7	18	61	1	14	93	0	3	100	0	0	?	14
		15	3000	50	7	21	67	0	14	100	0	8	100	0	2	100	19
1 in. = 150 ft.	1 in. = 150ft.	$6^2/_3$	1000	50	29	18	0	7	4	0	0	0	?	0	0	?	0
		10	1500	50	21	22	5	8	13	39	0	3	100	0	0	?	15
		$13^1/_3$	2000	50	10	19	47	1	9	89	0	3	100	0	0	?	21
		$16^2/_3$	2500	50	6	26	77	1	17	94	0	7	100	0	1	100	22
		20	3000	50	1	16	94	0	10	100	0	5	100	0	2	100	30
1 in. =100 ft.	1½ in. = 150 ft.	10	1000	50	21	32	34	5	5	0	1	0	0	0	0	?	8
		15	1500	50	14	29	52	4	14	71	0	1	100	0	0	?	15
		20	2000	50	4	14	71	1	4	75	0	0	?	0	0	?	8
		25	2500	50	5	26	81	2	11	82	0	0	?	0	0	?	32
1 in. = 75 ft.	2 in. =150 ft.	$13^1/_3$	1000	50	22	29	24	7	6	0	0	0	?	0	0	?	6
		20	1500	50	14	23	39	3	9	67	1	1	0	0	0	?	14
		$26^2/_3$	2000	50	7	21	67	0	12	100	0	3	100	0	0	?	35

TABLE II

PROTECTION AFFORDED BY SINGLE ROD

Summary of laboratory tests with various sources of potential when storm center is four times the rod height from a vertical line through the rod. On the scale used, the rod height is 150 ft. and the average cloud height is 2578 ft. With each source of potential 900 strokes were made with the rod and 900 without the rod. One rod height = h.

		D. C. (Pulsating)	A. C. 50 Cyc.	D. C. with Condenser	Surge Generator
Circle with Radius = 4 h	Hits with rod	227	256	261	125
	Hits without rod	401	386	415	397
	Per cent protection	43	34	37	69
Circle with Radius = 3 h	Hits with rod	74	76	67	31
	Hits without rod	198	168	148	183
	Per cent protection	63	55	55	83
Circle with Radius = 2 h	Hits with rod	15	7	2	3
	Hits without rod	77	63	47	65
	Per cent protection	83	89	96	96
Circle with Radius = h	Hits with rod	0	0	0	0
	Hits without rod	19	19	12	14
	Per cent protection	100	100	100	100
No. of strokes to rod		278	181	333	345
Per cent of 900 strokes to rod		31	20	36	38

TABLE III

PROTECTION OF A SINGLE ROD

Summary of laboratory tests when the storm center is twice the rod height from a vertical line through the rod. On the scale used, the rod height is 150 ft. and the average cloud height is 2578 ft. With each source of discharge used 900 strokes were made with the rod and 900 strokes without the rod. One rod height = h.

		D. C. (Pulsating)	A. C. 50 Cyc.	D. C. with Condenser	Surge Generator
Circle with Radius = 4h	Hits with rod	208	192	147	61
	Hits without rod	721	662	774	650
	Per cent protection	71	71	81	92
Circle with Radius = 3h	Hits with rod	129	108	134	16
	Hits without rod	562	501	614	495
	Per cent protection	77	76	78	97
Circle with Radius = 2 h	Hits with rod	39	26	45	3
	Hits without rod	318	263	332	264
	Per cent protection	88	90	86	99
Circle with Radius = h	Hits with rod	1	0	0	0
	Hits without rod	94	66	81	74
	Per cent protection	99	100	100	100
No. of strokes to rod		584	615	710	675
Per cent of 900 strokes to rod		65	68	79	75

will do, combinations of rods using 2, 3, 4, and 6 rods set on the circumference of circles were tried. Many tests were made with the rods grounded and connected to one side of the circuit, and an electrode above the center of the circle, on the circumference of which the rods were located. The rods took a large share of the hits, but it was entirely possible to make a portion of them strike the area within the circle when that circle had a radius of 4 rod heights. For smaller circles the number of hits inside was less. Also the protection factor increased with increase in sparking distance, or height of point above the plane of the rods.

Data about cloud height showed thunder clouds for Southern California to have a height of 2000 to 6000 ft. above the earth.[10] The preliminary work while far from complete suggested as a probable safe spacing of protective towers such that no portion of the area to be protected would be more than 2½ times a tower height from a tower.

To check this hypothesis, a model of one of the important storage farms to be protected was made to the scale of one inch equals 100 ft.

In making the protection plan, the model was tested first with towers only, the towers being adjusted as to location and height until it was practically impossible to make any discharges hit the miniature reservoirs. It was considered unnecessary to make it impossible to get a discharge to structures representing steel tanks. After the reservoirs were thus fully protected, some connecting cables were added at the 150 ft. level and another group of tests was made to test their effect. As a further precaution, each cable has, at the middle point of the spare between towers, a vertical cable extending downward from the aerial cable to the ground cable.

Each tower at its base, is grounded by means of a well drilled to permanent water and is also tied in to the water pipe system which is installed in such a way as to form a complete loop around each reservoir. The reinforcing steel of each reservoir is also connected to this grounding system.

In conclusion, it may be said that the authors feel that very good protection has been provided for the oil reservoir farms of California. It is urged, however, that more knowledge of lightning phenomena be gained as rapidly as possible. As a step in this direction many towers which have been erected are being equipped with fusible tips and klydonograph attachments to make it possible to get records of hits to towers.

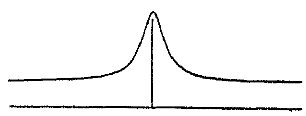


FIG. 11—EQUIPOTENTIAL LINE AROUND A CONDUCTING ROD UNDER A CLOUD

This plot was obtained by the formula quoted by H. V. Ingersoll in his thesis. The potential of any point (x, y) on the line is 5. The potential of the cloud is 100 and the potentential of the earth is 0. The height of the cloud above ground is 6.69 and the height of the rod is 1.22. In the plot the vertical scale is 2¼ times the horizontal scale.

Appendix

Inasmuch as grounded conducting towers do act as lightning rods, it would be natural to expect that some law of influence of a rod in space upon the electric field about that rod may be found. A search of literature for results of such studies and a series of tests to determine the effect of conducting rods upon an adjacent electric field were planned. The tests have not been completed and results which can be considered

10. Loc. cit.

conclusive have not been obtained as yet, but a large number of tests and two equations found in a thesis of H. V. Ingersoll, indicate something worthy of attention.

The equations are

$$\Phi = \frac{\Phi_2 - \Phi_1}{l\sqrt{2}} \sqrt{(y^2 - x^2 - d^2) + \sqrt{(y^2 - x^2 - d^2)^2 + 4x^2y^2}} + \Phi_1$$

and

$$v = \frac{\quad}{h\sqrt{2}} \sqrt{(y^2 - x^2 - h^2) + \sqrt{[-(y^2 - x^2 - d^2)]^2 + 4x^2y^2}}$$

The first of these equations was developed at the California Institute of Technology, whereas the second one is taken from a paper by Dr. Charles H. Lees published in the proceedings of the Royal Society of London, 1915.

In the first equation the following symbols are used:

Φ = potential at a point (x, y)
Φ_2 = potential at a cloud
Φ_1 = potential at ground
l = height of cloud above ground
d = height of rod.

In the second equation the symbols used are:

v = potential at a point (x, y)
h = height of rod
$\frac{\alpha\pi}{h}$ = vertical potential gradient at point (x, y).

If the vertical potential gradient is constant over the whole area then $\frac{\alpha\pi}{h} \; \frac{v_2 - v_1}{l}$

where

v_2 = potential of cloud
v_1 = potential of ground
l = distance between cloud and ground.

The equation now is

$$v = \frac{v_2 - v_1}{\pi l \sqrt{2}} \sqrt{(y^2 - x^2 - h^2) + \sqrt{[-(y^2 - x^2 - h^2)]^2 + 4x^2y^2}}$$

With Φ_1 and v_1 taken as zero and Dr. Lees' equation multiplied by π to get both equations in the same system of units the equations are identical.

Fig. 11 shows a curve plotted by use of these equations.

Figs. 12, 13, and 14 show charts obtained by means of a salt tray with one, two, and three rods respectively.

The salt tray used was 21 in. by 25 in. in size.

The bottom was a true plane kept level and then covered to a depth of ¼ in. with tap water.

Fig. 15 shows the arrangement used in making the tests.

An attempt was made to get from men with several years of experience at industrial plants, such as smelters with high stacks, located in places subject to considerable lightning reports of hits with relation to tall stacks equipped with lightning rods.

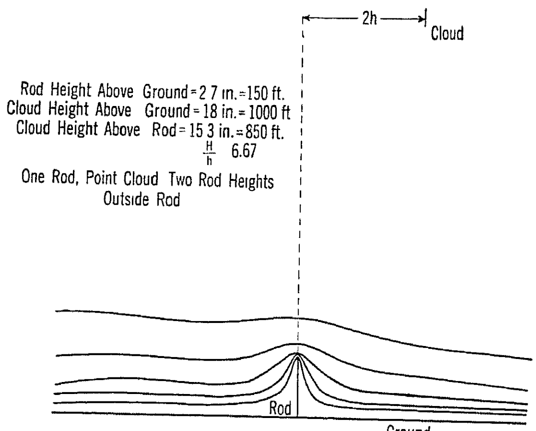


FIG. 12

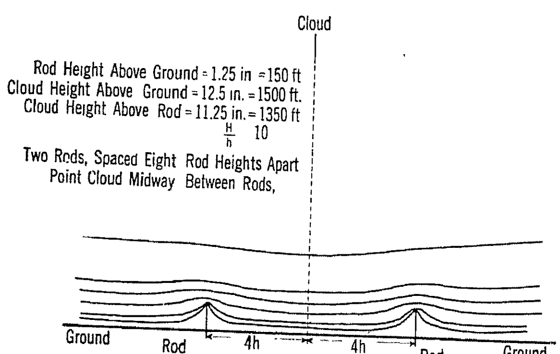


FIG. 13

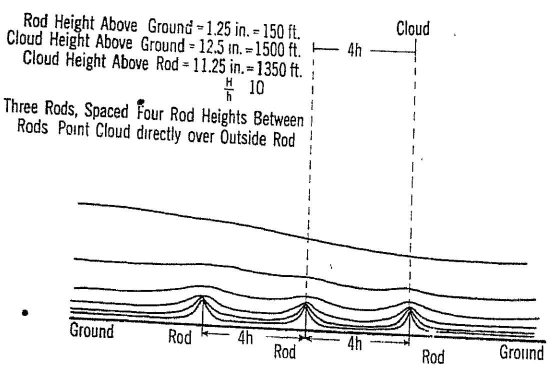


FIG. 14

FIGS. 12, 13, AND 14—EQUIPOTENTIAL LINES BETWEEN CLOUDS AND GROUND WITH DIFFERENT ARRANGEMENTS OF RODS

Charts plotted from tests made with salt tray shown in Fig. 15

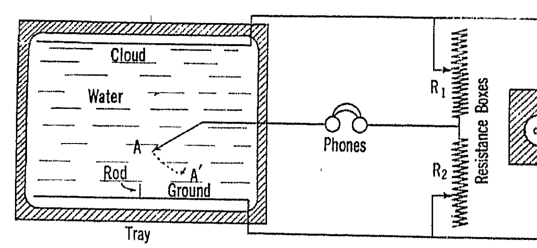


FIG. 15—DIAGRAM OF TESTS TO DETERMINE EQUIPOTENTIAL LINES WITH VARIOUS ROD ARRANGEMENTS

The reports are somewhat in disagreement and do not furnish material from which positive conclusions may be drawn, but there are a number of cases of reports backed by competent and careful observations which state that lightning often hits close to high stacks properly equipped with good lightning rods, without striking the rod.

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Discussion

For discussion of this paper see page 181.

Lightning Protection for the Oil Industry

BY E. R. SCHAEFFER[1]

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Synopsis.—*Building safe storage for the products of the oil industry is quite a different problem from making the storage already in use safe from fires started by lightning. The latter problem is discussed with some principles to be observed. Details of construction are so varied that it is difficult to give general rules. A record of several hundred installations over a period of about three years is given.*

Work with small models in the laboratory has been successful in some cases. It is unwise to rely too much on work of this kind, however.

Since the seat of the charge under a storm cloud is largely on pipe lines, tanks, and other metal parts in the oil fields, lightning devices should be securely attached to these structures. A network of pipe lines at or near the surface makes a better ground for towers than a single shaft driven vertically downward to permanent moisture.

* * * * *

Lightning Protection for Oil Storage

Any problem connected with lightning is difficult on account of the magnitude of the quantities involved. Because of the inflammability of hydrocarbons, the complexity of the operations, the great haste, and vast extent of the oil industry, any problem bearing on fire prevention in the petroleum field presents great difficulty. When we associate the two in an attempt to design protection against lightning for the oil industry, the problem is very complex and its solution will not be simple nor easily attained. Any hope of success in such an undertaking must rest on first-hand knowledge of the conditions under which fires most frequently occur, knowledge of details of construction, the varieties of construction used by different companies, special hazards arising from daily operations, and the effects of corrosion.

There are two distinct phases to consider; first, to design an oil tank which will be inherently safe against lightning; and second, to design a system which will offer a high degree of protection for the storage tanks *in actual use* today throughout the oil industry.

The solution of the first is easy and is probably exact. Theory and practise both indicate that the modern all-

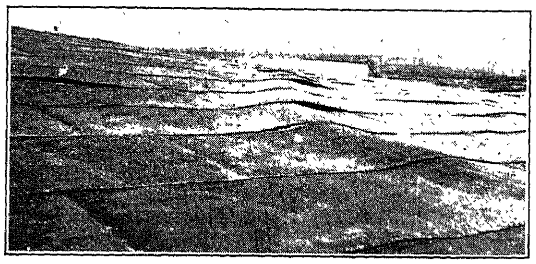

Fig. 1—Showing the Effects on Metal Sheets Nailed to Wood Decks Caused by Temperature Changes and by Filling and Emptying the Tank. In Many Cases the Effects of Corrosion are Just as Bad

steel, gas-tight tank is the best type of construction. The solution of the second problem is difficult and at best will result in an approximation, but for the present it is the more important. There are millions of dollars invested in unsafe storage tanks and the aim is to give this property the highest possible degree of protection and at a reasonable cost. It is the purpose of this paper to discuss the design and construction of protective devices for oil storage tanks now in use.

Oil is stored in various containers. The most common are steel tanks, spaced on 300-ft. centers, usually

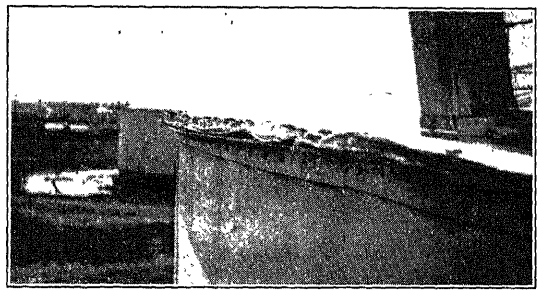

Fig. 2—A Minor Discharge Between the Roofing Material and the Vertical Steel Shell at the Eaves of a Tank which is not Vapor-Tight May be the Cause of a Fire

about 115 ft. in diameter, 30 ft. high, and having a capacity of 55,000 barrels. Although the tendency is definitely toward the use of steel decks for such tanks, a large number still have wooden roofs or decks, covered with sheets of galvanized iron or vapor-resisting paper and waterproofed fabric. In some localities, corrosion is so bad that steel decks last less than two years and only a wooden deck can be used. This is particularly true where the sulphur content of the crude oil is high. In California and also in the mid-continent field there are a number of earthern reservoirs most of which are lined with reinforced concrete and covered with wood decks similar to those used on tanks. Some of these are circular, having a radius of 250 ft. or more, while others are ovals of radius 300 or 400 ft. and length 600 to 1500 ft. The capacities run from 500,000 to 5,000,000 barrels.

It is common practise throughout the oil fields to gage and sample the oil from hatches on the deck. There are generally from one to four such gaging hatches per tank and there are several designs with various methods of closing but few of which can be considered gas tight.

If this brief description properly defined the problem,

1. Of the Johns-Manville, Inc., New York, N. Y.

Presented at the Pacific Coast Convention of the A. I. E. E., Del Monte, Calif., Sept. 13-16, 1927.

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much could be done in an experimental way with models. Unfortunately, however, there is a great mass of detail which seriously complicates the problem. Other tank fittings and arrangements of pipes vary so widely from one company to another that it is necessary to examine the design and installation of each company, and frequently of each tank, for appliances which are liable to give rise to sparks during electrical storms. Special hazards introduced by the location and character of structures near oil storage complicate the problem still further and discount any scheme of protection which is based entirely on the behavior of models of isolated miniature tanks and devices in the laboratory.

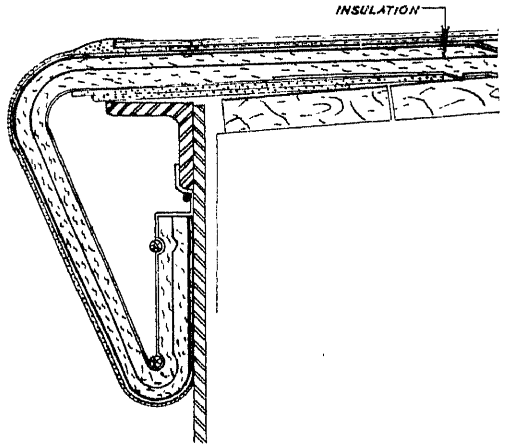

Fig. 3—Cross-Section of the Eaves Construction which is Flexible and Vapor Tight. It is Composed of Heat Insulation, Usually Hair Felt, and Roofing Fabrics

While the main lightning discharge is so powerful that it is liable to cause fires under any conditions, it is not necessary that an oil container receive a direct lightning discharge in order to cause a fire. Some years ago when little or no precaution was taken in the refineries against escaping gases, it was not uncommon to have a number of fires resulting from a single lightning flash in the vicinity of the refinery. Under such conditions, only a small spark is necessary to cause a fire, and it is well known that such sparks due to the surge of electric quantity across the earth's surface or to induction have caused fires at a considerable distance from the point which received the main discharge from the cloud. To illustrate, one large company erected a tower about 120 ft. high in one of its tank farms. A few weeks later the tower was struck and two tanks were fired, one tank about 200 ft. away and the other tank about 900 ft. from the tower. The disastrous fire at Monterey, California in 1924 was caused by lightning setting fire to a tank when the main discharge was received by a tree 780 ft. away. The reservoir fire at Coalinga in 1924 was caused by lightning although the actual flash was seen to strike on or near a pipe line about a quarter of a mile from the reservoir. The great reservoir fires at San Luis Obispo and at Brea, California in April 1926 were unquestionably caused by lightning. It is not known whether the latter fires were caused by direct hits or by minor sparks which accompanied the lightning discharge. The reservoir fire at Bakersfield a few weeks later was reported to have been caused by a direct strike of lightning which tore a hole in the deck. This reservoir was a simple earthern pit without reinforced concrete lining and it contained fuel oil.

It is impossible to say what percentage of oil fires have been caused by direct hits and what percentage by small sparks or secondary effects, but from the available data, it is reasonable to conclude that a large majority was caused by secondary lightning discharges.

Evidently, in the daily handling of large quantities of inflammable material and in the storage of such material in containers that are not actually gas tight, there is great danger that small sparks, which always accompany lightning discharges, may cause a fire even though the main discharge be several thousand feet away. Sparks caused by the surge over surfaces of varying resistance or along several paths of different impedance, when the earth's charge disappears at the instant of a lightning flash, are most certainly the cause of a majority of the fires and explosions in the oil fields.

In a general way, there are three conditions to fulfill for the prevention of fires on oil property set by minor discharges:

1. With the exception of one breathing vent, the containers must be kept closed,
2. Isolated pieces of metal in or near the vapor space must be grounded and all loose joints between metal parts must be eliminated to prevent the possibility of sparks,
3. The vulnerable areas should be enclosed by a Faraday cage or network, completely enclosing the non-metallic parts and securely grounded.

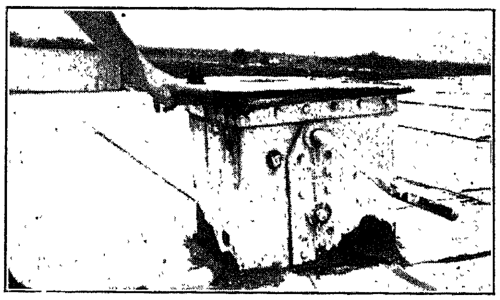

Fig. 4—A Winch Box on the Deck. The Cover is not Vapor Tight

When it is realized that all this must be done at small cost, without cleaning the tanks, and frequently when the tanks are filled with oil, the magnitude of the problem is apparent.

The design and construction of a suitable network or cage is the most important thing to be discussed here. Such a network was first designed and applied to wooden roofed tanks which had been covered with heat insulation and had been made vapor tight with flexible materials to prevent evaporation losses.

If a network of wires is placed under the heat insulation and roofing material, the wires would have to be very close together to prevent sparks between and below the plane of the wires, in or near the metallic fittings on the deck. There is danger also that when under storm conditions the charge on the deck is suddenly released by a lightning discharge, the roofing material may be punctured. This is particularly likely to happen at the edges of tank fittings or at the eaves where shallow pools of water may collect directly

Fig. 5—An Over-Shot Filling Pipe Passing Through a Large Hatch on the Deck

over the angle irons of the tank. If some material such as poultry netting is used there is great danger of sparks at the mechanical junctions where the netting is attached to the tank and at the edges of the strips of netting since all junctions must be purely mechanical. If a network of small mesh wire is placed directly over the roof and resting on it, there is the same danger of sparks occurring and, in addition, it would be again particularly difficult to deal with tank fittings where gases escape during changes of temperature of the vapor space or during the time the tank is being filled. Since only mechanical junctions are permissible, and these are very likely to spark during high-potential discharges, it is important that such junctions are not in a region where there is an explosive mixture of gases.

This factor, as well as the high cost of installing a network of small mesh and the danger that it would be damaged by workmen on the tank, made it necessary to consider a network of wires raised some distance above the deck. If wires were stretched across the deck it is necessary first of all that they be high enough so men can work under them. Since the purpose of the system of wires is to reduce the charge which may collect on the deck under storm conditions, and to provide a low-resistance path to ground when a lightning discharge occurs, the network must be grounded in a satisfactory manner. It should be securely attached to the tank itself and additional precaution should be taken to protect the eaves of the tank, since it is well known that most of the fires start there. The most obvious design then was a system of wires extending radially from a central wooden post at the peak of the deck to a cable supported above the eaves. This cable would have to be about 7 ft. above the eaves and supported preferably by metallic members attached to the tank as securely as possible without welding. It was necessary then to determine how far apart such wires should be and, if possible, to measure the degree of protection that such a distribution of conductors would offer, or at least find the ratio of the charge on the elevated conductors to the charge on the tank roof when a charged cloud was overhead.

Preliminary tests were made on a wooden platform about 12 by 20 ft. covered with hair felt and saturated paper similar to the construction for vapor tight tank roofs. This deck was set up 2 ft. above the floor in a large room with a system of four parallel No. 4 copper wires arranged 6½ ft. above the deck. The spacing of these parallel conductors was varied during the course of the experiments from a few feet up to the entire length of the deck. Above these parallel wires was a cloud of poultry netting, 10 by 24 ft., suspended from the ceiling by cotton tape. This netting was connected to one terminal of a large transformer; the other terminal was connected to the parallel wires over the deck. At one edge of the roofing platform, this grid was dropped vertically downward to the deck and grounded. The surface resistivity of the saturated paper on the deck was quite high when the surface was dry, being about 100,000 ohms per cm. This was reduced by a large factor when the paper was wet.

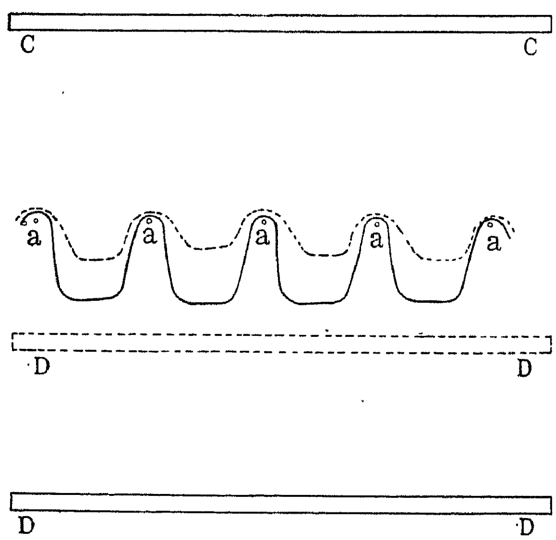

Fig. 6—Equipotential Lines in the Current Sheet. The Fraction of the Current which Flowed to the Grid ($a\ a\ a$) Indicates the Amount of Screening Produced by the Grid in the Electrostatic Case

A number of methods was tried for determining the potentials at points in the field between the deck and the poultry netting, particular attention being given to the region between the deck and the plane of the grid. None of the methods tried was considered satisfactory. However, equipotential surfaces were plotted and it was estimated, from the shape of these equipotential surfaces, that the amount of protection given was about 75 per cent.

The equipotential lines in a current sheet can be

easily studied and this gives a simple method for getting the required information. Accordingly, apparatus was set up to represent the cloud, a parallel grid and the earth in cross-section and the work carried out in a small horizontal glass tray. Referring to Fig. 6 $C\,C$ is the cloud, $D\,D$ the deck or plane to be protected and $a\,a\,a$ is the grid; that is, the points of intersection of the wires with the vertical plane perpendicular to the wires. The tray had a plate glass bottom about 24 by 36 cm. and contained dilute salt solution to a depth of about 0.3 cm. The cloud ($C\,C$) was a bar of brass and formed one terminal for the current sheet in the tray. The protecting wires ($a\,a\,a$) were small pointed brass rods screwed into a horizontal bar supported above the water. These rods were all adjusted in length so that they just touched the glass tray. The bar holding these rods was connected to the bar ($D\,D$) representing the deck and these together formed the other terminal. Using low voltage, 500 cycles, equipotential lines as shown in Fig. 6 were obtained by using a telephone receiver and exploring points.

When $D\,D$ was moved downward to the new position $D'\,D'$ the equipotential surface dropped down as indicated in the figure. In order to get some idea of the screening action of the grid, the bar holding the points ($a\,a\,a$) was disconnected from $D\,D$ and the currents which flowed from $C\,C$ to the grid and to the deck ($D\,D$) were measured. These currents were measured for a number of different positions of the cloud $C\,C$ and of the deck. Also the spacings of the points $a\,a\,a$ were changed. The ratio of the current flowing to $a\,a\,a$ and to $D\,D$ was taken to be the value of the protection offered to the plane $D\,D$ by the wires ($a\,a\,a$). This ratio was practically independent of the position of $C\,C$ so long as $C\,C$ was more than three times the spacing of $a\,a\,a$. It depended very much, however, upon the spacing between the wires ($a\,a\,a$) and the distance from these wires to the plane ($D\,D$). So long as the bar ($C\,C$) was some distance away from the grid the ratio of the spacing of the grid to the elevation above $D\,D$ determined the amount of protection.

Maxwell calculated the screening effect of a grating of equally spaced parallel wires on a plane surface parallel to the grating. This is the simplest case and is probably the only one that has been solved mathematically. The formula derived by Maxwell[2] gives the density of charge induced on the lower plane when the grating is interposed. The density of this charge is to that induced if the grating were removed as

$$1 : 1 + \frac{b_1\, b_2}{\alpha\, (b_1 + b_2)}\,.$$

where b_1 is the distance from the grating to the lower plane, b_2 the distance from the grating to the upper plane and α is a function of the spacing of the wires given by the following expression:

2. "Electricity and Magnetism," Volume I, Article 203.

$$\alpha = -\frac{a}{2\,\pi} \log\left(2 \sin \frac{\pi\, c}{a}\right)$$

Spacing of wires	Height of wires	Calculated protection
3 ft.	7 ft.	86 per cent
5 ft.	7 ft.	75 per cent
7 ft.	7 ft.	66 per cent
3 ft.	10 ft.	90 per cent
5 ft.	10 ft.	81 per cent
7 ft.	10 ft.	73 per cent
10 ft.	10 ft.	65 per cent

A large number of readings were made then with the current sheet to get values indicated for the protection offered by a grid. The percentages were all from 1 to 6 per cent higher than those calculated. While the experimental method is probably not capable of great accuracy, it did indicate a procedure for studying cases which are too complicated for mathematical solution.

The experiment with the current sheet is so simple and the results obtained were apparently so satisfactory

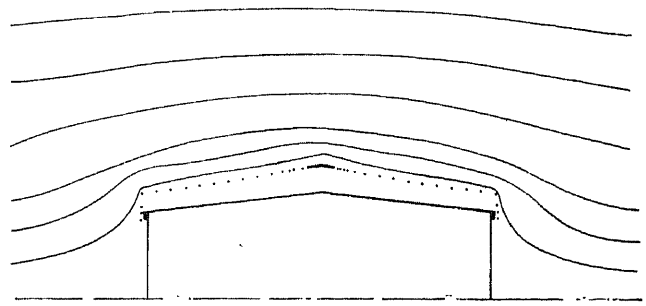

Fig. 7—Cross-Section of a Tank Protected by a System of Parallel Wires 7 Ft. or More Above the Deck. The Actual Model in Use was 2 Per Cent of the Diameter of a 55,000 Barrel Tank

that it was decided to study the cross-sections of details on a much larger scale. A large piece of plate glass 40 by 60 in. was used as a tray. A cross-section of a storage tank was inserted at the base of the tray over which was arranged a cross-section of the proposed network. The currents flowing to the cross-section of the deck and to the grid were again measured. In this case, the deck was receiving 13 per cent of the total current.

The records of tank fires show that in a large majority of cases, the fires start at the eaves of the tank. Accordingly, a large model of the eaves construction was made and the proposed plan for the grid installed in cross-section. Fig. 8 shows the reproduction of the equipotential lines traced for the eaves construction. It was not found possible with this arrangement to trace equipotential lines under the grid when the wires are placed very close together on the vertical bracket ($v\,v$). This model was made to scale, on the supposition that the cable at the top of the bracket was to be installed 7 ft. above the eaves and extend outward beyond

the eaves, about 3 ft. It is evident that a network must not only cover the deck but it must enclose it. While a fairly large spacing of the wires is probably satisfactory over the deck, the region over and around the eaves should be protected with a wire net of small mesh.

Since an actual installation gives a cage which is much more effective than a system of parallel wires,

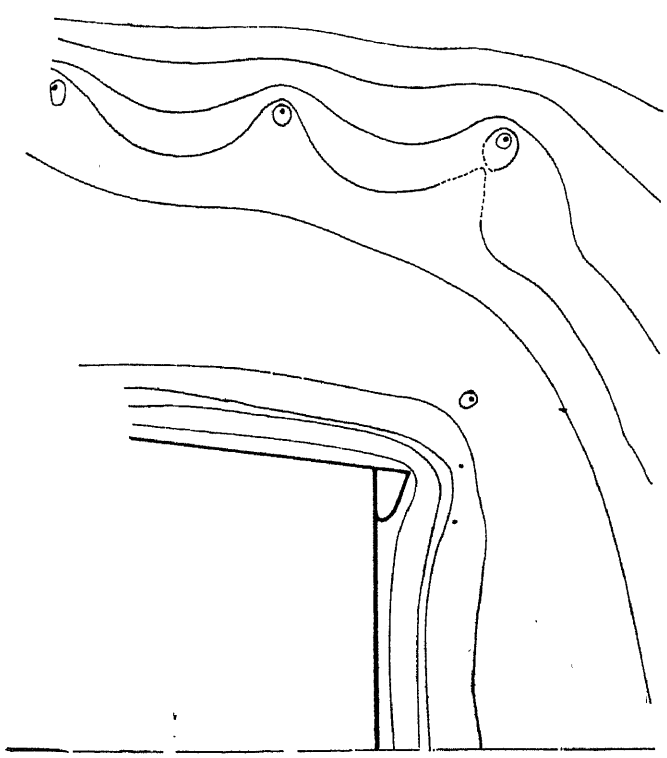

FIG. 8—EQUIPOTENTIAL LINES AT THE EAVES OF A TANK PROTECTED BY A SYSTEM OF WIRES. THE PROTECTION IS INCREASED BY PLACING WIRES CLOSE TOGETHER ON THE VERTICAL BRACKET $v\,v$

which this last model represented, it was necessary to build a model and devise a method for getting the effectiveness of a miniature network. So a tank model was made to be tested for the three-dimensional case. The tank was built of a wooden frame on the scale of 1 to 40 for the 55,000 barrel tank. Galvanized iron was used for the tank and a system of radial wires applied to scale according to the proposed scheme. The cloud consisted of one-in. mesh wire screening, 5 ft. by 10 ft. A vibration galvanometer was used merely as a sensitive a-c. ammeter to measure the charging current to the capacities formed by the network and the roof. Charging currents are proportional respectively to the capacities and to the charges that collect on the network and the roof. The results obtained this way were checked by using a ballistic galvanometer for comparing capacities. The ratio of the deflections gives directly the ratio of the charges desired. Measurements with the vibration galvanometer gave 96.8 per cent of the charge on the network. The ballistic galvanometer gave 98.4. This is the ratio of the charge which collects on the shell of the tank mode and the network to the charge which collects on the insulated metal tank top under the network.

Some tests in the field have been made to get an approximate idea of the efficiency of this network as actually installed on a tank. The attempts to measure the effect directly indicate that the efficiency is greater than 90 per cent. A more accurate result cannot be given on account of the difficulty of measurement and the crudeness of the apparatus used. The method consisted in measuring simultaneously the quantities of electricity discharged, at the time of the lightning flash, from a section of the network itself and similar conductors protected by the network. An improvement of this method will in all probability yield valuable information concerning the size of mesh necessary to reduce secondary effects to an even greater safety.

The ratio of the spacing of the radial wires composing the network to the elevation above the deck has a maximum value of five to seven over surfaces which are poor electrical conductors. The minimum value of the spacing was 18 in. at the eaves. Certainly this spacing of wires is too great unless conditions are very favorable. It is of the greatest importance to eliminate poorly

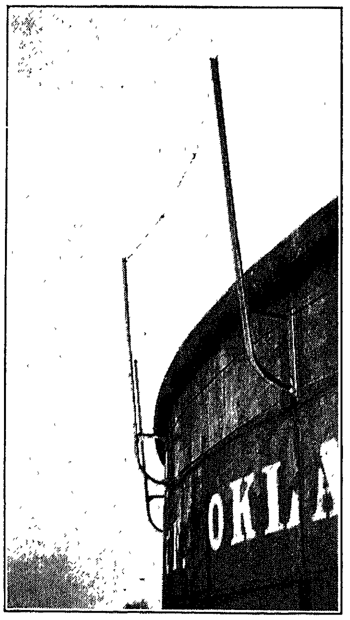

FIG. 9—DOUBLE ANGLE-IRON BRACKETS ON THE TOP RING OF THE TANKS HOLD THE PERIPHERAL CABLE TO WHICH THE RADIAL WIRES ARE ATTACHED

connected or isolated pieces of metal wherever possible. When this is not possible, it is necessary to use a screen of small mesh. The smaller the mesh the more complete the protection but the smaller the mesh the greater the cost and in most cases the greater the difficulty of application. Since most fires start at the eaves of the tanks it is advisable to increase the protection at this point. While the spacing of wires over the tank

proper may be satisfactory the spacing in the vicinity of the eaves should not be greater than 1 ft. Welded mesh wire with a 4-in. spacing should be installed on the steel brackets. This mesh wire should be 6 ft. wide and should extend completely around the tank at the eaves. The lower edge of this mesh should be at least one ft. below level of the angle iron on top of the tank shell. Above this width of welded mesh, No. 12 wires should be installed one ft. apart on the brackets and on the radial wires over the eaves.

If economy were not an important consideration many special problems and difficulties could be avoided by using a network of sufficiently small mesh. A grid of wires may reduce effects to a very small fraction but this may not be enough if the structure to be protected is fundamentally bad, or when operating conditions are such that fires may be easily started. A large quantity of gas is given out when crude oil is pumped into a tank and a lightning discharge near the tank at this time is very dangerous regardless of the protective devices. When oil is pumped out of a tank the air entering makes an explosive mixture and a very small spark will destroy the tank.

The over-shot pipe which passes through an open hatch is still in daily use in some places and may occasionally be used in emergencies by the most careful oil men. A surge along this pipe line is likely to cause a spark where the pipe passes through the tank roof and of course such a spark would ignite any vapors present.

In most cases the breathing vent is installed on the deck. These vents, fitted with fine mesh screens, are usually low but in some cases extend 5 ft. or 6 ft. above the deck, and, in one case, over 20 ft. This extension was made so that if the vapors catch fire the flames will be high enough above the deck to prevent setting fire to the roofing materials. Probably the most satisfactory solution here is to avoid anything over 4 ft. high and to install a net of 2-in. mesh wire on top of the grid composing the main network.

A large number of special problems have been considered during the past three years. Much experimental work has been done with models of tanks, of reservoirs, of gas collecting systems, and other construction details, using various types of electrical discharges. In some cases the results of work seemed to be definite and conclusive but in the majority of cases such experiments were unsatisfactory. Several investigators have made use of small models and unquestionably much of value has been learned in this way. However, one thing brought out very clearly during the course of this study was that the greatest care must be exercised in the interpretation of results in laboratory tests on models. It is quite possible to make a device or small model and apparently prove it satisfactory when experience under actual conditions shows it is not. Even though the models, cloud elevations, and voltage are reduced to a convenient scale, there are some factors which cannot be so reduced and, what is just as important, there are always conditions in actual practise which are quite impossible to simulate. Unfortunately, it takes several years to accumulate information in the field which could be obtained in a few weeks in the laboratory. But if the field record is from a large number of applications and the time includes sufficient number of severe storms the information is, of course, of prime value.

The network essentially as previously described has been installed on about 800 tanks during the past three years. These tanks are well distributed from Pennsylvania and New York, through Louisiana, Texas, Oklahoma, Kansas to California. The first and the largest number of installations was made in the mid-continent fields where the damages from lightning in the past have been very heavy. In a group where there are over 100 protected tanks, one tank was fired by lightning just two years ago. There have been no losses in this group since. In an equal period of time, including nearly the same number of storms, prior to the installation of the networks, nine tanks in this group were fired by lightning.

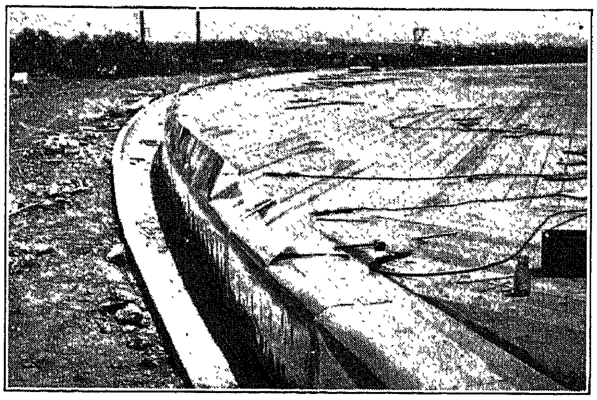

Fig. 10—Water Seal for the Eaves of a Large Reservoir in Course of Construction. The Trough is Concrete Reinforced with Welded Mesh Wire. Sheets of Zinc are Nailed to the Deck and Bent Downward into the Trough. The Wood Deck is then Covered with Roofing Paper

Several other fires have occurred on protected tanks, but always on tanks which, on account of operating conditions, were particularly susceptible, and which could not properly be considered to have a fair degree of protection. In two cases the hatches were open and the tanks were being filled with Oklahoma crude when the tanks received a direct lightning discharge. In two other cases the heat insulation and vapor tight roof had been installed over loose metal sheets. The oil had just been pumped out of these tanks leaving a mixture which exploded when struck by lightning, blowing the entire roof off the tanks. It is too much to expect a simple inexpensive network to protect tanks containing explosive mixtures and so constructed that there are numerous air-gaps between disconnected pieces of metal. Only one fire has occurred with conditions under which the network should have been effective.

In all other cases, the fires were due to changing conditions during the process of normal operation of moving the oil or due to causes otherwise avoidable. Eliminating those cases where for some reason the tanks were open, the reduction in the number of fires for a period of two and a half years amounts to over 90 per cent.

It is definitely known that some of these fires were started by primary discharges and it is probable that all were started in this way. Certainly some of the fires could have been prevented if towers had been used to protect the tanks from direct lightning discharges although in several cases recently reported, no fire was started when a direct lightning discharge was received by the network.

The large ground reservoirs presented new difficulties, but the enormous value concentrated into a relatively small space, justified greater expense in building a protective system. The cooperation of several of the California companies in working out details of construction, and their excellent scheme for reducing the oxygen content in the vapor space of the large reservoirs, by

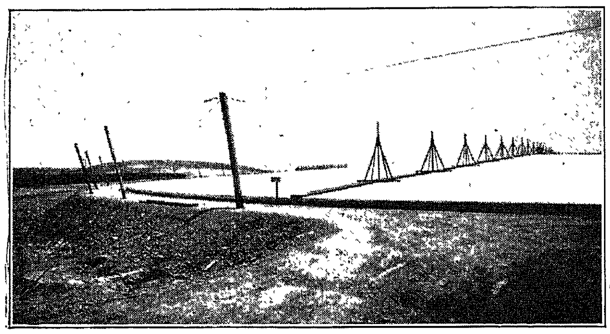

Fig. 11—Construction on the Embankment of a Large Reservoir Showing the Peripheral Cable, Grid and, in the Background, a Steel Tower

the introduction of flue gases, made possible a degree of protection of the highest order.

A million and a half barrels of oil may be stored under one roof, half underground, on about 10 acres which otherwise would require 30 tanks on at least 50 acres. These reservoirs usually have a lining of concrete reinforced with 6 by 6-in. welded mesh wire No. 6. The mesh is 10 ft. wide, lapped 6 in. on each strip and fastened together with short pieces of soft wire. This mesh wire is carried up to the eaves and is covered with concrete. The bottom of the reservoir usually contains several in. of water and above this the depths of oil may be as much as 30 ft. A number of pipe lines may lead into this reservoir, the main lines being usually 16- or 18-in. pipe. Surrounding the reservoir there is usually a three of four in. water line with fire hydrants, 300 or 400 ft. apart. Such pipe lines form the best means for grounding lightning devices.

The record of some appliances which have been in use for a number of years suggested that a peripheral cable grounded at frequent intervals is probably the most satisfactory and economical protection for the eaves of the ground reservoirs. If this is supplemented by a number of steel towers arranged around the reservoir, a high degree of protection should be obtained against primary lightning discharges. A grid of wires over, the entire deck would raise the charge under a storm cloud, above the deck and provide a path for the surge which otherwise would go over the deck when the cloud discharged.

Accordingly, telegraph poles were installed 40 ft. apart on the top of the embankment of the reservoirs about 12 ft. out from the eaves. These poles are 12 ft. above ground and are listed about 2 ft. outward from the reservoir. A 3/8-in. stranded steel cable is supported near the top of these poles and extends completely around the reservoir. One or more guy wires, extending from each pole, are connected to this peripheral cable the guy wires serving the double purpose of mechanically strengthening the system and affording good grounding connection. These grounds consist of metallic screw anchors and are all connected together by an underground copper cable which, in turn, is grounded to all of the pipe lines in the vicinity of the reservoir.

A detail map of an area that has been developed by an oil company shows a maze of pipe lines of many sizes, steel tanks, ground reservoirs and, in many cases, stills and steel towers if the storage is near a refinery. Evidently the charge on the earth under a storm cloud is distributed over these conductors and, when the cloud is discharged, surges travel along pipe lines and over wet ground toward the point where the lightning strikes. If this view is correct, towers, cables, and grids should be securely attached to tanks and to pipe lines on or near the surface. When a tower in this area receives a lightning discharge the charge on the earth's surface would collect principally on pipe lines and travel in a surge toward the tower.

A number of simple resistance measurements were made in the oil fields of Oklahoma, Texas, Louisiana and a number of places in California which indicated that the pipe lines were quite satisfactory for grounding lightning devices. In several locations resistance measurements were taken on the casing of water wells from 50 to 300 ft. deep. From these points it was established that pipe lines were well grounded and from the latter a number of tanks were found to make good contact with the earth. Although several hundred measurements have been made, in no case has it been found that the resistance of a pipe line to ground, or of a steel tank amounted to more than half an ohm.

It is sometimes considered necessary to sink a shaft 50 ft. or more, to permanent water, to establish a good ground for lightning towers. Surely this can do no harm, but it is doubtful if there is information which indicates that it is necessary.

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Discussion

LIGHTNING PROTECTION FOR OIL STORAGE TANKS AND RESERVOIRS

(SORENSEN, HAMILTON AND HAYWARD)

LIGHTNING PROTECTION FOR OIL TANKS

(SCHAEFFER)

DEL MONTE, CAL., SEPTEMBER 16, 1927

R. J. Reed: I should like to say just a word regarding some field work in which six of the oil companies on the Coast have cooperated during the past summer. It seemed wise to erect, at a location where we might expect a great many lightning storms, several towers similar to those now protecting a number of oil reservoirs in Southern California. Carson Spur, a high ridge in the Sierras 25 mi. south of Lake Tahoe, was chosen. As soon as the snow was off the ground five steel towers were erected, instruments were installed, and observations were carried on during the summer. Near the towers small structures simulating reservoir roofs were constructed, but these were not protected with grounded conductor network as described in Dr. Schaeffer's paper. Unfortunately we have no results to report as there were practically no storms this year. We shall go on with these observations during another year with the hope that there may be lightning storms and that some of our towers will be struck.

With respect to the combination of direct-hit towers and grounded conductor network installed for protection of oil reservoirs as described by Dr. Schaeffer, we have had the following experience. At our Stewart Tank Farm, near Brea, California, during a severe lightning storm on December 8, 1926, two towers received direct hits. These towers were situated adjacent to 750,000-barrel reservoirs filled with light refining crude oil. The evidence of the direct hits is the report of eyewitnesses who were so stationed as to see the towers readily, and who state that one tower was struck and that within a few minutes the other tower received a direct hit. No damage was done either to the protective equipment or to the reservoirs. So far as I am aware this is the only field test of protective equipment of this type.

M. E. Dice: Sparks caused by induction seem to be responsible for more fires in the petroleum industry than direct strokes of lightning. It is not enough to protect oil-storage containers against direct hits; they must also be protected against secondary effects. The records of Dr. Schaeffer's adaptation of the Faraday cage in Louisiana indicate that it is meeting with success. Lightning towers erected in Southern California at the location of a disastrous fire in April 1926 were struck by lightning eight months later, at which time a combination of towers and networks prevented any damage to the remaining reservoirs.

Two conditions must be present if ignition is to occur by induction, the occurrence of a spark and the presence of flammable material. The authors of these papers have discussed chiefly the elimination of the spark. Let me emphasize the importance of preventing a flammable or explosive vapor in oil tanks. Practically all Pacific Coast petroleum companies have taken this precaution, accomplishing it by refining the crude oil formerly stored in earthen reservoirs, placing all volatile fractions in safe all-steel gauze-vented tanks, and returning only the heavy non-volatile fuel oil to the reservoirs. Where refinery capacities will not permit this, the oxygen content of the vapor above crude oil in reservoir is decreased by the constant addition of washed flue gases to the point where ignition is impossible. Sparks, however produced, are incapable of damage if there is nothing for them to ignite.

Professor Sorensen's paper mentions the effect of the insulating properties of oil in deflecting to the edge of the reservoir strokes which might otherwise hit the center. This applies only when the reservoir is not roofed or is covered with a dry non-conducting roof. If the roof is wet, as it is many times during thunderstorms, the oil is covered with a conducting sheet and the dielectric effect of the oil is decreased or nullified.

In the measurements of current discharged from sharp points, it is well to remember that the voltage gradients reported are the average gradients between the upper plate or "cloud" and the lower plate or "ground." The actual gradient at the tip of the needle is the one in which we are interested, and it could not be measured. The actual gradient at the point is considerably higher than the average.

Measurements of the electrostatic field distribution by electrolytic methods are valuable in many problems, but they fail when the field about a sharp point is to be mapped. The electro static and electrolytic fields are not the same in the immediate vicinity of a discharging point.

Table I should not be taken too seriously. It was quoted more or less at random as an example of many such tables and should not be used alone for the design of tower systems because the conditions of the tests reported were quite limited.

Close scrutiny of the table reveals serious differences due to changing the scale of operations. We were unable to eliminate scale differences but were reassured by the fact that as the scale increases or approaches full size, the degree of protection increases. Therefore we hope for as much as, if not more protection under actual lightning conditions then in the laboratory.

The summaries shown in Tables II and III are likewise affected by scale differences. The actual values shown have little meaning. They indicate only that various circuits give widely different results, or that laboratory lightning is not a standard article. Better protection was obtained when the surge generator was used than with other circuits. This is encouraging, because the surge generator is thought to be the best laboratory analogy of lightning now available.

The translation of laboratory lightning data into full-scale magnitudes has not been accomplished with any degree of certainty. It is to obtain full-scale data for this purpose that we have established an observatory which we call the "Camp of the Cooperating Competitors" in the High Sierras.

E. H. Wilcox: (By letter) The paper, "Lightning Protection for Oil Storage Tanks and Reservoirs" seems to indicate that the prevention of lightning by the establishment of proper convection discharge from ground to cloud is impossible. I am glad of the opportunity to offer the following for consideration:

Speaking of the proposal to prevent lightning discharge by prevention of the accumulation of sufficient charge on cloud and earth to cause a discharge between them, the author says:

"There are no known records of this having been accomplished . . . although there have been many schemes suggested."

He further states:

"If conduction current great enough could be obtained, there

would be a possibility of keeping the potential between earth and clouds down to a value too low for the discharge by lightning." With this last statement we are in perfect accord, as it is in line with our own experimental conclusions, provided that he would consent to change the word *conduction current* to read *convection current*, inasmuch as the process by which this is accomplished is not conduction along a metal or other conductor, nor along a path that has been made conducting by reason of a lightning flash, which lightning flash itself has been made possible because of the intense localized and concentrated ionization which has created a conductive path between cloud and ground.

A convection current, on the other hand, does not create such a conducting path, but by reason of its distribution in space prevents such local concentration of ionization as to cause conduction.

The experiment, as shown in Fig. 5, is practically a duplication of one of the earliest of our own experiments, but as we soon learned, has no relation to the question of how much current can be dissipated by convection on a properly designed system.

Were it proposed to afford protection by setting a few points over a reservoir or tank, insulating each point from the roof of that tank, then there would be some reason for this experiment. As far as I know, no one has ever proposed such a method of protection, although Von Diest in his suggested method approximates this most closely, but it is one that does not interest us. Our experiments on this line were that we might perfect a chain of investigation rather than as an end in itself, although we did carry it to the point of experimenting with up to 1000 points in a shielded field.

Here our results come into approximate alinement with those shown in Fig. 7, if he will change the word "conduction current" on the left-hand margin to read "convection current."

Study of the curves and tabulation in Fig. 7 shows that all the author's experiments maintained a constant ratio in the variables of the set-up:

	Cloud ht. in.	Point ht. in.	Point spacing in.	Current flow microamperes per point
1..........	12	1.0	4	4.7
2..........	6	0.5	2	1.6
3..........	3	0.25	1	0.2

and yet that the current flow increased with dimensions as shown above in the final column, at corresponding gradients (80 kv. per ft.). Here he has the whole matter in his hands, but throws it away. He says "but it is inconceivable that the same order of increase of current with increase of scale will be maintained up to the scale of clouds and lightning towers in actual use." We should like to say "Why?"—especially as the curve is still a rising one and shows no suggestion of flattening out.

We would suggest that the speaker carry out extension experiments using the same ratio of cloud height, point height, and spacing and increasing the cloud height say by steps to 144 in. all at a gradient of 80 kv. per ft., and then note the curve of current flow. Then as a variant he might change the spacing of the points and note the results. Of course to do this he would probably have to use alternating current, but the charging and capacity components of the observed flow can be extracted vectorially, leaving only the convection discharge.

In spite of this, for a reason which he does not explain he elects to use an arbitrary figure of 2.5 microamperes per point in certain calculations. He also seems to feel that his spacing of points at four times their height is the ideal although, as he shows on the sixth page, second column, no absolute protection exists even within the 1-1 ratio.

In view of his limited experiments and the concession that his calculations may be largely in error it scarcely seems worth the while to discuss his computations on the fifth page. As a reduction *ad absurdum*, had he assumed a 6000-ft. cloud he would have asked for the same number of towers but 500 ft. in height and 2000 ft. apart; or with a 24,000-ft. cloud, towers 2000 ft. high and 8000 ft. apart, denying by inference that any intermediate towers or points would have an amelioriating effect.

One question, however, we should like to ask, in view of his computation, that 2,500,000 towers are required to afford protection: Was the speaker correctly quoted in the press reports of January 10th (United News Leased Wires) in which he was credited with recommending: "an extreme lightning rod consisting of 150 to 175 towers placed near the tanks to be protected?"

I find that to rearrange the points shown on Fig. 5 into a peripheral ring instead of concentrating them in a massed position in the center of the field raises the current as dissipated by convection many times, and also that the overcrowding of points, even into a peripheral field results in a diminution of total current. This particular line of investigation was not carried to great lengths, as it was only a connecting link between the dissipation from such a shielded point as referred to by the author, and points arranged on a closed cordon of wires.

On such a cordon which is representative of the protection system as actually adopted, we find the dissipation of convection current *per point* varies with the potential gradient of the field, the number of wires in the field, and the length and spacing of points on the carrier wires.

The following table will show the results of one experiment. In this 12 points were arranged on a single ring 30 in. in diameter, or approximately 7.85 in. apart, and the potential gradient raised to values shown below, with the following convection current discharge per point:

Potential gradient in volts per cm.	Total convection current in microamperes	Flow per point in microamperes
494	3.2	0.27
614	9.8	0.81
770	32.0	2.66
985	68.0	5.65
1360	153.0	12.7
1650	222.0	18.5
1970	480.0	40.0

These were all with direct current, neither pulsating nor rectified. The final gradient is considerably less than one-half the danger gradient. From a study of the above it is evident that a figure in excess of 100 microamperes per point would have been reached before approaching the danger zone.

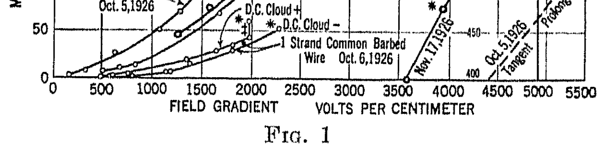

Fig. 1

In another experiment with a single point in the field, in a gradient of 80 kv. per ft., a discharge of 780 microamperes was recorded.

Fig. 1 herewith shows the actual dissipation or convection current as measured for a one-wire and for a three-wire system. Our opinion is that the form and spacings of points on the wire and the method of attachment of points is of considerable

importance, but we have not sought to follow this in detail experimentally, simply selecting the longest and sharpest points obtainable and specifying that points should be welded to the carrier wire, or that the wire be regalvanized after assembly of points.

It will be noted that on curve $a = 4.4$, November 17, 1926, actual convection currents to the value of 475 microamperes per lineal foot of system were measured; a tangent prolongation of this curve to the flashover value promises that over 650 microamperes per foot may be expected.

A comparison of curves $a = 9.7$ and $a = 3.7$ October 5, 1926, with the ascending curve of discharge as recorded by Professor Sorensen on his Fig. 7, confirms our opinion that the scale may be a very important factor, and suggests that actual discharge may reach a much higher value than any recorded in the laboratory.

We further find that the total current flow with 12 points arranged in 3 close groups of four is practically identical with that from 3 single points, indicating that arrangement and spacing, rather than number, is the important thing.

In all our experiments we were compelled to work at comparatively low gradients, as we did not wish to risk the danger of a flashover which might have been ruinous to the microammeters in use, hence this limitation.

It soon became apparent that the intelligent unit to use in any such investigation is not the value per point, but the value per lineal unit, for any given spacing. Further experiments, however, showed that there was comparatively little difference in the totality of convection current from a given system, whether there were two, three, four, or five wires in that system, provided that the over-all spacing between wires 1 and 5 remain constant. Or in other words, removing wires 2 and 4 from a 5-wire system only raised the unit value per wire, the totality at a given gradient remaining practically constant. An increase in the spread of the wires resulted in an increase in totality. A decrease of spread reduced the totality. This is by reason of a partial interference of the convection currents from the several wires.

Theoretically, I believe that as good practical results could be achieved on a well designed two-wire system as on one with multiple strands, although the multiple system has the advantage of giving rather lower gradients in the immediate vicinity of the points, and insures that the mechanical breaking of a single wire does not affect it unduly.

The assumption of the author seemed to be that the entire charge of the cloud should be discharged to effect protection. This is not our conception. A discharge that will balance the charging rate of a cloud, or even a discharge that will balance the charging rate for the last portion of discharging period, is all that is necessary to prevent the potential gradient reaching the flashover point. It takes only a small relief valve on a boiler to prevent its blowing up, even though the fires be not drawn.

Table I is interesting and certainly affords food for thought. One question immediately suggests itself. With the center of cloud discharge vertically over a point which is four tower heights away from the tower, why should there be any discharges within a circle of 1 or 2 tower heights from the tower? The remarkable part of this experiment is the number of strokes that fell within these circles in spite of the set-up. How any strokes at all fell within this zone with the additional protection of a tower, only shows the vagaries of lightning discharge.

We accept without reservation his conclusion:

"Results of the tests made for all types of discharge used show no absolute immunity for any area around a rod."

We are not able to accept equally his statement:

"Considered from a statistical viewpoint, the number of hits within a circle having one rod height as a radius and with its center at the rod was practically nil"

in view of his succeeding clause:

"But there was an occasional hit even within this area which was not taken by the rod.

His experiments here were scarcely sufficiently numerous for so broad a generalization."

I should, however, point out the essential difference from an oil man's standpoint in the attitude regarding the percentage of protection. Granted that 99 strokes out of 100 in a given case might be taken by the towers, and only 1 taken by the protected object, yet that does not mean a 99 per cent protection. It means 100 per cent risk, as we have only to wait for 100 discharges to have occurred before disaster will have overtaken us, but we have no assurance whether it will be the first or the 50th, or the 99th stroke that will do the damage. To a statistician the protection may be 99 per cent; to an oil man it is zero.

All the thought of the speaker seems to be toward averting direct strokes. No well informed man questions that this can be done in very large measure by any intelligent tower system. Oil men know, however, that the majority of oil-field and oil-tank lightning fires are not caused by direct strokes at all, but by secondary discharges, due to the release of the hitherto bound charges simultaneously with the primary discharge.

No system of rods or towers affords or even pretends to afford protection from these dangerous secondaries.

All oil companies today endeavor to limit these hazards by the avoidance of explosive or inflammable mixtures in or around tanks to lessen this danger. Some of the methods used are expensive, both in installation and maintenance, and may fail at the needed time.

We have experimented in many ways to find a method of controlling these secondaries in the presence of primary; frankly they are all failures. Our deliberate judgment is that the only certain protection against secondaries is to prevent the occurrence of primaries.

S. S. MacKeown: I want to point out a very interesting bearing that the paper by Professor Carroll and Mr. Lusignan[3] has on the matter of preventing lightning by discharge from points. Professor Carroll pointed out in the discussion that where he was using a rectifying d-c. voltage the peak of his current came approximately a quarter of a cycle after the peak of his voltage. That is, it took approximately a quarter of a cycle for the current to move from the wire out to a cylinder. The distance from wire to the cylinder was 7½ in.

If then we did assume that a sufficient discharge was dissipated from points to neutralize a cloud, that charge would travel to the cloud with a very limited velocity. The velocity is very readily obtained from the work of Mr. Carroll. It differs for different potential gradients; but if we take the value for 42 kv.—given on his Fig. 9,—we find it takes a quarter of a cycle to travel 7½ in.; that is, about 150 ft. a sec.

Now, the average distance of a lightning cloud is about 2400 ft., and average rate of time to charge up is about 10 sec. If then we assume that these ions travel with this same velocity from the points up to the cloud, they would not reach the cloud in time to prevent a lightning discharge.

When you consider also that the cloud is usually moving at a fairly large velocity due to wind, if the charge should reach the cloud, it would reach it at some point other than over the district sought to be protected.

J. T. Lusignan, Jr.: In the work carried out at Stanford University last year a rectified space charge was found to be built up in the ionization process about a point in a-c. corona. With a point in a unidirectional field, as that of a rod below a thunder cloud, this effect would be more marked, as a copious supply of ions of one sign would surround the point when the field intensity becomes sufficient there to start ionization. This "cloud" of ions would tend to shield the point and reduce the field intensity there in such a way as to cut off materially the

3. *The Space Charge that Surrounds a Conductor in Corona,* J. S. Carroll and J. T. Lusignan, Jr., p. 50.

supply of ions that, with the cage system of lightning protection, must go up to the thunder cloud of opposite polarity to discharge it.

Mr. Dice made a very apt comment on the need for care in applying to the field the results of laboratory studies of protective arrangements and reduction of cloud charges by points. It must be remembered that although the heights of the cloud and rods, and the size of the tanks may all be brought down to scale, the ion used in the laboratory is the same ion that is involved in the lightning stroke, and its size and velocity cannot be brought down to scale. Accordingly, it is problematical how closely its behaviour and path in the laboratory follow those out under a cloud. It would seem obvious on the other hand that the larger the laboratory set-ups, the nearer conditions in practise would be approached, a fact which Peek has seemed to realize fully in his endeavor to use as large laboratory models as possible.

H. P. Miller, Jr.: (communicated after adjournment) There is a marked similarity between the design of protective networks for oil-storage tanks and the design of ground systems for high-power transmitting antennas. A storage tank is screened so that if it is struck by lightning the steep-wave-front impulse is led off to ground through a low-resistance path. An antenna ground system provides low-resistance paths for radio-frequency currents going into the ground plate of the antenna, which is simply a large radiating condenser. Many of the same design considerations will therefore apply in both cases.

In a transmitting antenna the ground system is designed so as to minimize the impedance of conducting paths from all parts of the ground to the radio transmitter. Using conductors of low resistance is not always sufficient since their reactance may be so high as to force the currents off through some medium of high resistance. It is therefore desirable to use direct leads from a large number of widely scattered ground points to the transmitter. Applying these principles to the protection of an oil-storage tank would mean the use of conductors from the center of the tank to a large number of buried connections around the outside of the tank.

The method described by Mr. Schaeffer for protecting steel tank meets these requirements except for the ground connections around the outside. The use of such an arrangement might not be economical but would help considerably in keeping the strong field away from the edges of the tank where fires are so likely to start.

Mr. Dice has called attention to the fact that the laboratory investigations with a salt bath give the electrolytic field and not the electrostatic field. From a study made by the writer in connection with the insulation of guyed masts[4] it would appear necessary to map the electrostatic field by means of a convenient sized model.

R. W. Sorensen: I am sorry Mr. Wilcox is not here to present his discussion in person for I should like to have him explain how he made the tests upon which he bases his proof that our results are absurd. Inasmuch as we cannot have that presentation I fail to see the advantage in taking up valuable time to defend each detail of our paper which for some reason Colonel Wilcox has seen fit to attempt to disprove, and I will make no defense of our work other than to say that, though we know it is incomplete, we have to date found no disagreement with the results we have presented and results which have been obtained by other engineers experienced in conducting high-voltage experiments.

The work which we have reported and which was done at California Institute of Technology was made possible only by the cooperation of the oil companies, who contributed the cost of the work, and the engineers of these companies who assisted in doing that work. For their cooperation and that assistance we are indeed most grateful, but we hope that means will be provided so that this work may be continued until such results which have been presented are checked and further data have been obtained.

The object of the program which formed the basis of this paper was not the development of some commercial project to be sold to oil companies for financial gain, but was purely a scientific project to enable the oil companies to obtain protection in every way possible and to further the scientific knowledge as to the performance and character of lightning. In presenting this paper we have wished to bring out for discussion certain facts learned to date and in this we think we have been fairly successful.

Secondly, it is our desire to encourage more groups of people working in high-voltage laboratories to take up the problem because we think definite results will be obtained more rapidly if the problem can be attacked by several groups who do their work at different places; in fact, we are convinced that if a number of groups had attacked the problem sooner there would be more knowledge and agreement as to the exact character of the phenomena.

We also feel certain, as a result of this work, that we can now analyze places to be protected and devise systems of towers and overhead networks used alone or in combination which will give a very large degree of protection, the amount of protecting obtained being entirely a question of economics. In doing this, however, we are also quite certain that no means can be provided which will be very successful in a lightning district in preventing the occurrence of strokes, (of course there are others who differ from this and we seem to have two authentic records—one of my correspondents has told me that a tall smelter keeps away lightning because there has been no lightning within five miles of the stack, and we found that the towers which were erected at Carson Spur this summer have been so effective that the three or four towers have kept all lightning from occurring in the High Sierras during the summer). There were also rumors and reports in the press that a barbed wire entanglement erected in France had kept away lightning strokes. At my request Dr. John Whitehead, of Johns Hopkins University, investigated the report as to this protection while in France and informs me he can find no record of its having been successful or even of its having been tried out to any great extent. I think, therefore, we have sufficient basis for our statement that lightning strokes cannot be prevented by the erection of a barbed wire fence, even if the barbs are large.

In conclusion, therefore, may I point out that protection can be obtained, first, by having all inflammable materials completely caged in all-metal tanks; if tanks which are not all-metal are used, only heavy non-inflammable residuum fuel oils should be stored therein, and if lightning may occur near such oils these reservoirs should be guarded by towers approximately 200 ft. high and so spaced that the distance between towers is not more than five tower heights, the tower height being the height of the tower above the top of the object to be protected.

Of course the supreme method of protection has not been mentioned; that is, keep the oil in the ground until needed. This, of course, can only be done when some method is developed which will enable the oil companies to control production. There is no danger of oil in the ground being ignited by lightning stroke.

We have considered carefully all the points mentioned as to scale effect, and we have drawn our conclusions with full knowledge of the limitations of our work due to that effect.

Another point is, we find that on the Pacific Coast we should be very grateful for our freedom from more frequent lightning strokes. One place I visited in the East this summer had the lights go off twelve times in one afternoon because lightning interfered with the transmission lines. In districts where lightning is as prevalent as that it is easy to understand why some power companies are talking of extending all towers well

4. "The Insulation of a Guyed Mast", by H. P. Miller, Jr., *Proceedings* Institute of Radio Engineers, March, 1927.

above the transmission lines and stringing a number of ground conductors for the sole purpose of obtaining protection against lightning.

In conclusion may I say that the problem is still wide open and the more groups interested in it, particularly in our colleges, the better. In order, however, to bring about this condition, the college groups will need assistance in financing their work by the industries interested in obtaining protection.

C. D. Hayward: The phenomenon of the conduction of electricity through gases by means of ions is one which has been known and studied for many years. The idea of applying this phenomenon to the prevention of lightning is also not new. There is at least one case on record where it was tried in France a few years ago using a grounded system of barbed wire similar to that proposed by Mr. Wilcox. This system was later abandoned, probably because of failure.

Granting that conduction of electricity through gases is a different phenomenon from conduction through metals, and granting that the flow of currents from pointed conductors through a gas differs from an arc or spark discharge in that in the former case the gradient is high enough to cause ionization by collision only in the immediate neighborhood of the pointed conductor while in the latter case ionization occurs along the whole path of the discharge, still the use of the term "conduction" to cover all these has become established by usage in physics and I doubt if it would be possible to change the term to "convection" now even if it were desirable to do so.

Near the beginning of his discussion Mr. Wilcox makes the statement: "Were it proposed to afford protection by setting a few points over a reservoir or tank, insulating each point from the roof of that tank, then there would be some reason for this experiment." Mr. Wilcox does not seem to understand that the needles and the ground plate were at the same potential since the needles were connected to the plate through the low-resistance micro-ammeter as may be seen by examining our Fig. 5. The only reason for insulating the needles at the point where they pass through the ground plate was to cause the current flowing off the points to pass through the micro-ammeter.

Mr. Wilcox has not given enough data on the dimensions of his apparatus to enable anyone to compare the results given in his discussion with those given in our paper. He does not give the height of the 12 points mounted on the 30-in. ring nor does he give the height of the cloud electrode above the points. He does not give the shape of his cloud electrode nor does he tell whether or not he used a grounded plate under the 30-in. circle to represent the earth surface. It will immediately be apparent to anyone familiar with electrostatic fields that these factors will affect the potential gradient in the air near the points not simply a matter of a few per cent but several hundred per cent. Since the potential gradient is what determines the current flow it is easy to see how Mr. Wilcox might be able to get large currents from the points by using certain extreme forms of apparatus. Data of this kind are useless because these extreme forms of apparatus cannot be duplicated in the field. We cannot change the shapes of the clouds and the earth to suit our fancy. When making the tests described in our paper, we made the proportions of the model such that they could be duplicated in the field. Assuming a 2400-ft. cloud, which is a good average for the height of storm clouds, the points would be 200 ft. high, which is about the maximum height that towers can be erected without too great an expense. We placed the points at a distance of four times their height apart because we found from a study of the electrostatic fields that this was as close as we could place them without having the gradient in the air near each point greatly reduced due to the electrostatic shielding effect of neighboring points. It is of course necessary to keep this gradient as high as possible in order to obtain the maximum current flow from each point.

Near the end of his discussion Mr. Wilcox gives what to his mind is a difference between the attitudes of an oil man and a statistician regarding the percentage of protection afforded by a given protective scheme. He says that to an oil man no protective scheme gives any protection unless it gives 100 per cent protection. This seems to me to be a very peculiar attitude, because reducing a risk in the ratio of 1 to 100 certainly means something to an engineer, and most of the men holding the higher positions in the oil companies are good engineers.

132,000-Volt, Single-Conductor, Lead Covered Cable

Introduction, Economics and Commercial Demand

BY P. TORCHIO[1]

Fellow, A. I. E. E.

Synopsis.—*This paper, which describes the development of the oil-filled type of 132,000-volt cable, has for convenience been divided into four parts.*

In the first part the economic and commercial aspects of the development are discussed. It is pointed out that this type of cable permits direct interconnection with high-voltage overhead lines and it is felt that the satisfactory operation of the two lines which have been placed in service this year will be an indication that 220,000-volt cable can be constructed without material changes in the design.

The theory and design of the cable are completely developed in the second part. Particular reference is made to the effect on the dielectric of occluded gas and the method of eliminating trouble from this source in the oil filled type is described.

The third part relates to the manufacture, inspection, and testing of the cable and equipment. The tests showed that the electrical constants of the cable were substantially unchanged by the normal temperature cycle.

The installations at New York and Chicago are described in the fourth part. Inspection, indication of oil leaks, cable and joint repairs are discussed. The replacement of a length of the New York cable, which developed a leak in the sheath, is covered in detail.

* * * * *

WHILE the power generated from local plants in heavy centers of industry and population is distributed locally at about 13,000 or 25,000 volts, system interconnection lines and long-distance transmission lines require considerably higher pressures in the order of 66,000, 132,000, and 220,000 volts.

In most situations of heavily built-up centers, it has been impossible in the past to tie the higher voltage lines directly to the distributing stations and substations, and recourse has been made to underground cable lines of 33,000, 45,000, and 66,000 volts connecting to the higher voltage overhead lines through transformers located at substations on the outskirts of the city. One of the principal aims of the design of the new type of cable, which by one step doubles the highest underground operating voltage used heretofore, is to do away with these outside intermediate substations by bringing the higher voltages directly to the ultimate distributing centers. The economic and operating advantages thereby obtainable are savings of intermediate substations, transformers, switchgear and attendance, reduction in number of underground cables, savings in synchronous condensers, increased efficiency, improved regulation, and improved stability of parallel operation of local plants with the outside sources of power. The final relative values of these savings will not be available until we have secured from actual experience the relative carrying capacity of the oil-filled cables in contrast with the ordinary type of cables with solid insulation.

The theory of the oil-filled cable is that through its collapsible oil reservoirs it responds readily to volumetric changes in oil and cable due to temperature changes. In this manner, the whole cable is kept constantly filled with oil under pressure both in the hollow core of the conductor and throughout the surrounding insulation. The unique advantage of this type of construction, therefore, is that should the lead sheath be expanded or distorted, or the internal elements of the cable be displaced by temperature variation or other causes, the spaces thus formed will be immediately filled with oil, while in a solid insulation type voids would be formed, causing ionization and ultimate failure. It is thus evident that this new type of cable should be able to operate safely over a much larger range of copper temperature and therefore of load, than a solid insulation type, even if the latter is operated only at 66,000 volts or less. In this expectation we are confirmed by the original installation of this type of cable made in Italy three years ago, which consisted of about 2000 ft. of line connected in series with a 130,000-volt overhead transmission line more than 100 mi. long. This cable, which was 50 sq. mm., about 100,000 cir. mils, in cross-section, has never given the slightest trouble though carrying currents of 250 amperes per phase, a current density which would be absolutely impossible with the solid type of cable even if operated at 25,000 volts or less.

The Chicago 132,000-volt underground cable line is a direct application of the plan of connecting a generating plant in the city to an outside 132,000-volt line six miles away.

The New York 132,000-volt cable is, for the time being, a large capacity, 12-mi. length transmission line supplying the large county of Westchester in the state of New York, but it will in future serve also to interconnect with outside sources of power supply.

The Chicago and New York installations were placed in operation, respectively, on June 2nd and August 9th, of this year, and have since operated without electrical trouble.

The manufacturers feel that should these two 132,000-volt cable lines continue to prove satisfactory in opera-

1. The New York Edison Company.

Presented at the Regional Meeting of District No. 5 of the A. I. E. E., Chicago, Ill., November 28-30, 1927.

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tion, 220,000-volt cable can be constructed without material changes in the design of cable, joints, and accessories.

The next year's experience of the large New York and Chicago installations appears now almost certain to prove satisfactory, in which event this great advancement in the art will have made available to the industry, confronted with unprecedented volume of growth in its demand for power, means not heretofore available for transmitting hundreds of thousands of kilowatts economically and directly to and from centers of heavy population and outside supervoltage overhead lines.

In the following chapters the manufacturers and the users are presenting a complete description of all the phases of work involved in the design, manufacture, and installation of this radically novel type of cable.

Theory, Design and Development of the 132,000-Volt Cable

BY L. EMANUELI[2*]

Non-member

General. It is well known and recognized that one of the principal reasons of failure in high-tension cables is the presence of gas bubbles and films in the dielectric, some of these gas occlusions being left in the insulation during the construction of the cable and some being formed later during the operation of the line.

This is due to many facts. First, the vacuum applied to the cable before impregnating it with insulating compound is not generally perfect. Second, the insulating compound carries in solution a great volume of gas, part of which is set free while the compound is passing through the paper during impregnation. Third when the lead sheath is applied to the cable, the cable is still rather warm and the subsequent thermic contraction of the compound when the cable cools down causes further voids. Empty spaces are also created when the cable is coiled on the reels and during handling.

When the cable is in operation, another important phenomenon takes place. The insulating compound is warmed up and increases in volume when the cable is loaded and this first compresses the gas in the dielectric and then expands the lead sheath. As the lead is more viscous than elastic, after a subsequent cooling the total amount of void space within the dielectric is greater than before installation by an amount proportional to the load carried.

For example, in a 66,000-volt cable, the contraction which follows an increase of temperature in the copper of 35 deg. cent. causes a volume of seven gal. per mi., (16 liters per km.) to be emptied of compound.

The pressure which may take place in a cable when loaded, and which forces out the lead tube, has been found by actual measurement to be in the neighborhood of 90 lb. per sq. in.

Seasonal temperature variations produce the same effects.

Where is it that these empty spaces are formed? In a general way, we can assume that they are produced at the points where the paper is less compact, in the wrinkles, in the space between the lead and the insulation, especially where the lead is expanded due to bends or handling and, for three-conductor cables, in the spaces between the insulated conductors and the fillers.

This may be explained when one thinks that the surface tension of the compound has a tendency to fill up first the smaller cavities, thus leaving empty the larger ones.

In addition to this, the compound has a tendency to migrate to the lowest points of the cable and this migration is greater the lower the viscosity of the compound.

This irregularity in the distribution of the gas cavities is one of the principal causes of the many uncertainties in the results obtained in the laboratory and during operation, and makes it impossible to fix an exact figure for the permissible value of the ionization as a function of the working voltage.

The failure of all the previous attempts made to explain theoretically the breakdown voltage on a sample of cable, in connection with the electric gradient in the insulation, can probably be attributed to the presence of gas occlusions and to their irregular distributions, and perhaps the theory which gives the breakdown voltage as a function of the minimum gradient and not of the maximum, is not to be completely discarded, the minimum gradient being near the lead where the empty spaces, at least for a single-conductor cable, have a greater tendency to be formed.

If the empty spaces due to the thermic contraction of the compound were formed uniformly in the insulation, in small units, the troubles produced by their ionization would be very small. A step toward this point has been gained by the cable manufacturers by wrapping the paper on the conductors as uniformly as possible, and avoiding wrinkles and registration of the layers.

It is also evident that the greater the thickness of the insulation, the smaller is the possibility of avoiding such empty spaces during construction. In addition to this, if the contraction of the insulating compound should be such as to distribute uniformly and in small

2. Società Italiana Pirelli.

*Acknowledgment and thanks are made here to Dr. E. Sacchetto who has given his assistance in the first experiments on the oil filled cable and in the installation of the Brugherio cable, Mr. E. Sesini who has assisted in the theoretical design of the cable and accessories, and Mr. M. Puritz who, with Mr. Sesini, has directed all the delicate operations of installation and impregnation of both the New York and Chicago lines. Acknowledgment is also made of the valuable assistance and cooperation rendered by the engineers of the General Electric Company and of the New York and Chicago Companies during all these latter operations.

units the empty spaces which are formed, then the quality of a dielectric would be independent of its thickness; but, due to their localized formation as a consequence of capillarity and drainage, the probability of leaving big empty spaces is greater the greater the volume of the dielectric, and accordingly of the amount of oil subject to volumetric change. We can

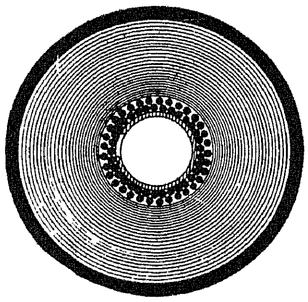

Fig. 1—Hollow Core Cable

assume, therefore, that an increase in the insulation thickness does not produce a corresponding improvement in operating performance; and the cable manufacturers know this very well.

All these difficulties and uncertainties would not have allowed the design of a 132,000-volt cable of the usual type with any probability of success and the results which may have been obtained in the laboratory and in the field on short lengths of cable would have been practically worthless due to variations in the distribution of the gas occlusions.

It must also be considered that the experience gained on a large scale on existing cables is limited to a voltage which is only about one-half of 132,000 volts. It was with the idea of avoiding all these uncertainties, eliminating gas occlusions as much as possible and especially the ones which are formed by temperature variations, that the writer designed and carried out the construction of the oil-filled type of cable.

The principle is very simple and consists in having the cable connected to a reservoir which will receive the oil pushed out during the thermic expansion and give it back to the cable during the contraction. To obtain this action, it is necessary to have inside the cable a passage which connects the reservoir with every point of the dielectric. This feature can be obtained readily by stranding the copper wires of the conductor around a metal spiral, thus leaving a single central passage, see Fig. 1, or by shaping the lead sheath as shown in Fig. 2, thus making several longitudinal paths which can be connected to the reservoir. This eliminates the danger of formation of empty spaces due to the contraction of the oil.

The presence of a longitudinal path makes possible the evacuation and impregnation of the cable from both ends after it has been leaded. On account of its small volume, laboratory pumps can be used and a very high vacuum reached. In addition to this, a special process has been worked out to purify the oil from the gases in solution, before impregnating the paper.

In this way it is possible to obtain a cable practically without any occluded gas from the start and also to maintain it in such condition during operation.

An experiment on a cable of the type given in Fig. 1 was made early in 1918 and the results were quite surprising. The life tests gave results far better than those on usual cables and it appeared immediately that the importance of a perfect construction of the cable as referred to wrinkles and compactness of the paper could be regarded as secondary.

It is important to remember that in a cable made in the usual way, the breakdown voltage is very high if the voltage is increased quickly and does not give any light on the punctures which happen in operation at a voltage generally equal to, or slightly higher than, the operating voltage. If the tension is applied for several hours, the breakdown voltage is considerably smaller, and the longer the time of the test, the lower the breakdown voltage. It is not difficult, for instance, to get a breakdown voltage on a short sample, after a few seconds, which is five times greater than that found after several hours of application of voltage.

In the oil-filled cable these differences were found to be much smaller, and as the instantaneous breakdown voltage is equal to, if not greater than, that on usual cables, the breakdown voltage after several hours is more than doubled. This permits increasing the operating gradient of the cable and the use of only a small thickness of insulation.

Another advantage over other cables of the usual type is to have much smaller dielectric losses at high temperatures because it is possible to use a very fluid oil with very small power factor, as the danger of migration of the compound is avoided.

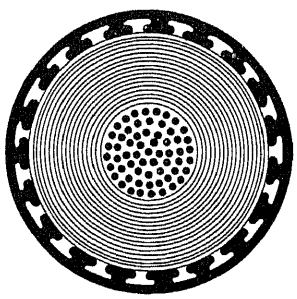

Fig. 2—Slotted Sheath Cable

For several reasons a field test of this new type of cable was not made on a large scale until the end of 1923 when a line of three cables of 100,000-cir. mil (50-sq. mm.) copper area, 670-mil (17-mm.) insulation, each 2000 ft. (610 m.) long, with six joints, was installed at Brugherio near Milan, Italy, connected to an overhead line about 100 mi. (160 km.) long. In the beginning the cables did not carry load, but in 1924 they were put

in series with the line and a load up to 250 amperes per phase was carried without any trouble for two and one-half years.

The electrical problem of the construction of a cable for 132,000 volts was in this way solved quite satisfactorily but several mechanical problems, especially complicated for lines of long length and with large differences of level, remained to be studied.

Mechanical Design of the Line. The first problem was to determine the most suitable dimension to be given to the hollow central passage as related to the viscosity of the oil and to the length and profile of the line. The oil which must flow from the feeding reservoirs to the various points of the cables is subjected on its way to friction and, if the distances are not properly calculated, an excessive pressure may take place in the cable when applying a sudden load, or empty spaces may be created for a short time, during cooling.

Let us consider first the problem of the cable which cools down and let us call a the quantity of oil which, at a certain moment, the cable absorbs per unit of length (centimeter) and per second. Calling q the flow of oil along the central passage and x the distance of the point from the end connected with the reservoir, we have

$$a = -\frac{d\,q}{d\,x}$$

and then

$$q = -a\,x + q_0$$

Calling l the total length of the cable, the flow of oil at the end opposite to the feeding end ($x = l$) will be zero and we have

$$q = a\,(l - x) \tag{1}$$

Let us assume that the friction of the oil in its movement along the tube is proportional to the flow, which can be considered as true for very slow movements.

Calling b the coefficient of friction corresponding to the shape of the central passage and to the viscosity of the oil, we have the drop of pressure, $d\,p$, on a length of core $d\,x$,

$$\frac{d\,p}{d\,x} = b\,q \tag{2}$$

and from (1)

$$\frac{d\,p}{d\,x} = -a\,b\,(l - x)$$

Integrating,

$$p = -a\,b\left(l\,x - \frac{1}{2}\,x^2\right) + p_0$$

where p_0 is the pressure at the feeding end of the line, this formula being true only for a perfectly flat profile cable.

If the cable is not on a level, calling h_x the difference of level between the point x and the feeding end of the cable, (h being positive if the point x is lower than the feeding end) and γ the specific density of the oil, we have

$$p = h_x\,\gamma + p_0 - a\,b\left(l\,x - \frac{1}{2}\,x^2\right)$$

For practical purposes, it is better to express p in units of length of the oil head which let us call h and h_0 the value corresponding to p_0. We have, then,

$$h = h_x + h_0 - \frac{a\,b}{\gamma}\left(l\,x - \frac{1}{2}\,x^2\right) \tag{3}$$

It can be seen readily, applying the formula (3) with different values of a and b corresponding to various dimensions of the central core and oils of different viscosities, that it is not possible to feed long lengths of cable from a single feeding point because the pressure in the distant portions of the cable would drop so much as to create a vacuum inside the core and the dielectric.

For this reason it is necessary to divide the cable into a certain number of sections, each separately fed, stopping the passage of oil between them. The length of a section to be fed from one point has been determined graphically from the formula (3) assuming that the oil pressure during the cooling period should never be allowed to drop in any point of the cable below a certain figure, and this value was fixed to be the atmospheric pressure, $h = 0$.

The formula (3) for $h = 0$ and $x = l$ becomes

$$h_x + h_0 = \frac{a\,b}{2\,\gamma}\,x^2 \tag{4}$$

In this expression, the quantity $\frac{a\,b}{2\,\gamma}\,x^2$, which we will call H, gives the drop of pressure, in units of length of the head of oil which takes place along a length X from the feeding end.

Let us take the profile $A\ B\ C$ of the line, Fig. 3, on a certain scale, X being the lengths and H the elevations, and plot to the same scale the curve 1, $H_1 = \frac{a\,b}{2\,\gamma}\,x^2$, which gives the drop in pressure, the center of the coordinates corresponding to the center of the feeding reservoir F, and the positive direction being downwards. The curve of the profile of the line $C\ B\ A$ gives the static pressure of the oil at any point referred to the atmospheric pressure in units of head of oil, when the oil is supposed not to move.

The point A at the distance X_a where the curve 1 cuts the profile of the line, determines the length of a section, for at this point we have the dynamic drop of pressure equal to the static head.

It is necessary, however, to be sure that this condition is repeated for every point of the section. Taking $h = 0$, $l = x_a$, $h_x + h_0 = H_a$, the formula (3) becomes

$$H_a = \frac{a\,b}{2\,\gamma}\,x_a^2 \left\{ 2\,\frac{x}{x_a} - \left(\frac{x}{x_a}\right)^2 \right\} \qquad (5)$$

which gives the drop in pressure in every point of the section of a length $l = x_a$.

Curve 2, passing through F and A, is plotted from this formula and the pressure of oil in any point of the cable during the cooling period is readily obtained as the

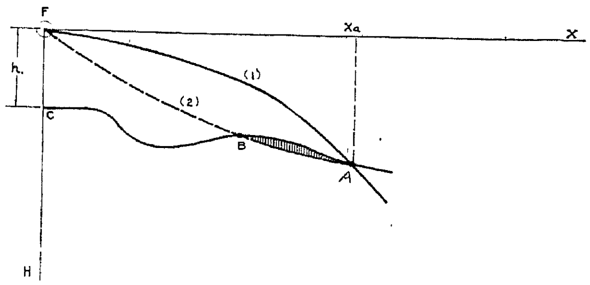

FIG. 3—STATIC PRESSURE DIAGRAM WITH FEEDING TANK ONLY

difference between this curve and the one of the profile of the section. For instance, in Fig. 3 the pressure of oil along $B\,A$, (shaded area) would drop below atmospheric.

In the preliminary study of the line, the lengths of all the sections were determined from the curve 1, taking into account the position where the feeding point could be located on the ground, and also that the pressure in a section, under equilibrium conditions, should not be more than a certain value.

Curves similar to curve 2 were plotted for each of the sections, thus determining the portions of the section where, due to the profile of the ground, the pressure would be below the prescribed value.

For these portions, where possible, the profile of the conduit was changed by increasing the depth of the duct bank. In some instances, this was not possible and the length of the section had to be shortened.

In some other instances, however, practical considerations did not permit cutting down the length of the sections to the value calculated from the curve 1, and it was therefore necessary to give to the section an extra length. Evidently the part of the section beyond the point A of curve 1 will not comply with the prescribed pressure conditions. In such cases, it was necessary to install a second supply of oil at the lower end of the section. This was done by means of special oil tanks, called pressure tanks.

The pressure tank consists of a strong metal tank full of oil, which has inside a certain number of air-tight cells, with collapsible walls, full of gas. The tank is connected with the lower end of the cable and for this reason the oil in it and the gas inside the cells are subjected to the pressure corresponding to the static head of oil from the reservoir.

When the cable cools down, the pressure at the far end of the section drops below the static head and the gas enclosed in the collapsible cells increases in volume, and pushes out the oil from the tank into the cable.

In Fig. 4, F is the feeding point, $C\,A$ is the maximum length of cable which can be fed from F, determined as explained above, and P is a pressure tank.

With these conditions, the section is fed from both ends, having the feeding tank at one end and the pressure tank at the other. At the first moment of cooling, the pressure tank is subjected to a hydrostatic pressure given by the head of oil from the feeding reservoir and acts exactly as an open tank connected at the lower end of the section, at the same level as the feeding tank. In this first moment, therefore, half of the cable will be fed by the feeding tank and half by the pressure tank.

The curve calculated from formula (4) will apply also to the pressure tank and will have to be plotted from the point B, at the same level as the feeding point F, see Fig. 4, in opposite direction. But after a certain length of time, the pressure inside the tank and in the gas cells will be smaller on account of the volume of oil having been fed back to the line. The corresponding curve will have to be plotted not from a point at the same level as the feeding reservoir but from a point at the level lower than B by a quantity h_1. This curve will cut the curve from F at a point D which divides the section l in two parts, one fed from the feeding tank and one from the pressure tank.

The equation of the new curve will be

$$h = \frac{a\,b}{2\,\gamma}\,(l - x)^2 + h_1$$

The point D where this curve cuts the curve

$$h = \frac{a\,b}{2\,\gamma}\,x^2$$

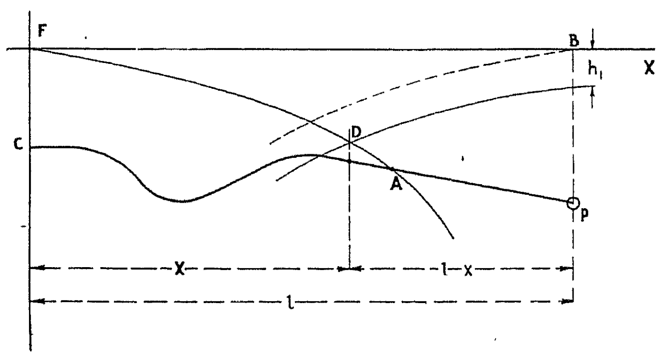

FIG. 4—STATIC PRESSURE DIAGRAM WITH FEEDING AND PRESSURE TANKS

plotted from F, will be given by eliminating h from these two equations, *i. e.*,

$$x = \frac{1}{2}\,l + \frac{h_1\,\gamma}{l\,a\,b}$$

The length of cable fed at that moment from B will be

$$l - x = \frac{1}{2}\,l - \frac{h_1\,\gamma}{l\,a\,b}$$

If we consider a certain interval of time, dt, the length of cable fed by B will absorb a volume of oil

$$a\,(l - x)\,dt$$

This volume of oil is given by the pressure tank and the volume of gas in its cells will accordingly increase by a quantity $d\,v$ equal to the amount of oil given out,

$$d\,v = a\,(l - x)\,dt$$

and substituting,

$$d\,v = a\left(\frac{1}{2}\,l - \frac{h_1\,\gamma}{l\,a\,b}\right) dt$$

Calling p_1 the hydrostatic pressure of the pressure tank at the beginning of the cooling period and p the pressure at a certain moment, we will have

$$h_1\,\gamma = p_1 - p$$

and thus

$$d\,v = a\left\{\frac{1}{2}\,l - \frac{p_1 - p}{l\,a\,b}\right\} dt$$

From the characteristic equation of gases

$$p\,v = p_1\,v_1 = K$$

we have

$$d\,v = a\left\{\frac{1}{2}\,l - \frac{p_1 - \dfrac{K}{v}}{l\,a\,b}\right\} dt$$

Integrating this equation between the time zero, beginning of cooling period, and a time T, we have:

$$\int_{V_1}^{V} \frac{d\,v}{\dfrac{1}{2}\,l - \dfrac{p_1 - \dfrac{K}{v}}{l\,a\,b}} = \int_0^T a\,d$$

This supposes a to be constant during this time which is a condition of greater safety.

The second integral is nothing else than the volume required by the unit of length of cable when cooling down from the temperature at the time zero to the temperature corresponding to the time T. Let us call it Q.

Solving the first integral, we obtain:

$$V_1 = \frac{A\,Q}{\dfrac{B}{A}\log_e \dfrac{B - A}{B - A\dfrac{V}{V_1}} - \dfrac{V}{V_1} + 1}$$

where

$$B = \frac{p_1}{l\,a\,b} \text{ and } A = B - \frac{1}{2}\,l$$

For $A = 0$, the above expression gives a result equal to zero and therefore is of no use. One of the ways to solve the problem is to suppose $A = 0$ before making the integration and then we have the result,

$$V_1 = \frac{2\,B\,Q}{\dfrac{V^2}{V_1^{\,2}} - 1}$$

which gives values practically exact also if A is not zero but only small with respect to B.

This expression was used to calculate the volumes V_1 of the gas in pressure tanks when at the pressure p_1 and thus the volume of gas at atmospheric pressure to be contained in the cells.

Up to this point, only the drop of pressure which takes place in the cable when the load is dropped, has been considered.

The increase of pressure which is caused by the oil expansion under load can be studied very simply by changing the sign of coefficient a in all the formulas written.

If the line is calculated in such a way that during cooling the pressure never drops below atmospheric, it is easy to see that during the heating period the pressure will increase to a value about double the hydrostatic head.

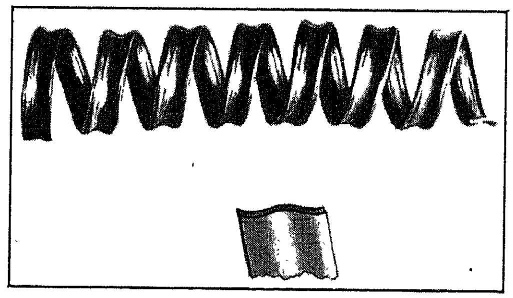

Fig. 5—Copper Spiral for Hollow Core Cable

Determination of Coefficient b. As no data were readily available on the movement of viscous liquid inside a tube, a series of experiments was conducted on a lead tube immersed in a water bath at different temperatures, the flow of oil being supplied by a reservoir at a certain height over the tube; the drop of pressure along an established length and the times required by a certain quantity of oil to flow out were measured. It was found that within the limits of the viscosity of the oil to be used and for the flows to be expected in the cable, the drop of pressure could be considered proportional to the flow and the formula of Poiseuille was exact enough for the purpose.

Experiments were made also on the effect of a metal spiral inside the tube and after several tests it was recognized that in order to reduce, to a minimum, the resistance to the flow, it was advisable to use a supporting spiral of very small thickness. The spiral shown in Fig. 5, made up from a specially shaped copper tape so as to give the required mechanical strength, was adopted.

Calculation of Coefficient a. The variations of temperature in the cable due to load variations are of much

greater importance than those due to variations in the temperature of the surrounding medium, and coefficient a is calculated on this base.

Let us suppose that the cable is working at a certain load and that W watts per unit of length are dissipated from its external sheath. When the load is removed, the temperature of the outside surface will remain for a certain length of time the same as under load and the same number W of watts will be dissipated. These watts will be given out by a corresponding cooling down of the internal points of the cable. For a first approximation, we may calculate the value of a per unit of length assuming that the watts dissipated by the load are equal to the sum of the various products of the specific heat of each elementary volume of cable by its corresponding drop of temperature.

The cable may be divided into three parts:

1. The copper conductor and the oil contained in the tube and between the wires. This part may be considered as all at the same temperature, on account of the high conductivity of the copper and the fluidity of the oil. Let us call c_1 its average specific heat, v_1 its volume, and T_1 the temperature at a certain moment.

2. The insulation where the temperature varies from point to point. Let us call c_2 the average specific heat of the paper and the included oil, $d\,v_2$, the elementary volume in a point, and T_2 its temperature at a certain moment.

3. The lead; in this first approximation let us consider only the interval of time during which the lead temperature practically does not change; we can then forget about it. This, of course, neglects the lead losses.

We may then write

$$W = C_1\, v_1 \int \frac{d\,T_1}{dt} + C_2 \int \frac{d\,T_2}{dt}\, d\,v_2 \qquad (6)$$

If we call E_1 the volume of oil absorbed by each unit of volume of the part 1 of the cable, for one degree temperature variation, and E_2 the corresponding volume for part 2, we can write that

$$E_1\, v_1 \int \frac{d\,T_1}{dt} \text{ and } E_2 \int \frac{d\,T_2}{dt}\, d\,v_2$$

represent the total volume of oil absorbed by the conductor and by the insulation, for every second, at that particular moment.

If we call the first expression a_1, and the second a_2, we may from (**6**) write

$$W = a_1 \frac{C_1}{E_1} + a_2 \frac{C_2}{E_2}$$

which is not sufficient to calculate $a_1 + a_2$.

We can consider, however, that in the very first moment after the load was removed, only the conductor will begin to cool down and that therefore

$$a = a_1 \text{ or } W = a \frac{C_1}{E_1}$$

It is then possible to calculate readily the initial value of a. It is interesting to note that this value is independent of the surrounding medium and depends only upon the number of watts which are dissipated.

After a short time the value of a will be an average between the initial value corresponding to the copper conductor alone

$$\left(W = a \frac{C_1}{E_1} \right)$$

and that corresponding to the insulation,

$$\left(W = a \frac{C_2}{E_2} \right)$$

It is evident that when the lead starts to cool down, the watts dissipated will also diminish and thus also a will accordingly decrease.

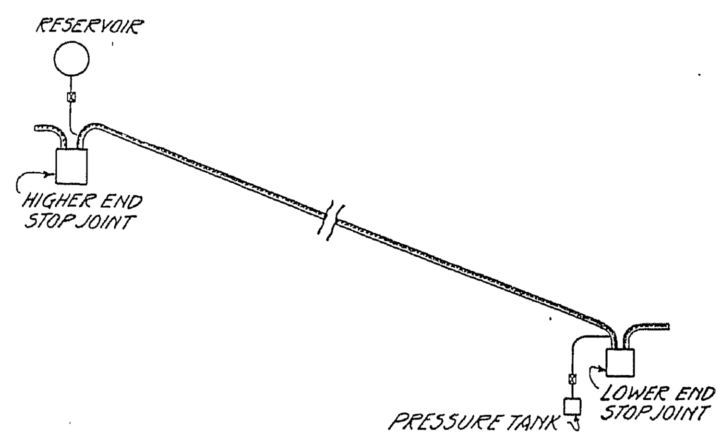

Fig. 6—Schematic Diagram of Cable Section

For sake of safety in the design of the cable, the greater of the two values corresponding respectively to the conductor and to the insulation has been chosen. The lead losses have been included in W and while their effect on coefficient a is rather complicated they have thereby been amply provided for. On this basis it was possible to calculate the dimensions of the cable. As said above, it was found necessary to divide the total length of the line into various sections each separately fed by oil reservoirs. With the exception of a few sections where the length was determined by the maximum hydrostatic pressure of the oil in the cable on account of the steep grade of the profile, the length of the sections was calculated assuming a certain diameter of the central passage, taking the value of a for the corresponding cable and of b in the conditions of minimum winter temperature, maximum viscosity of the oil, and then plotting the length of the sections in the graphical way described above.

Keeping in view the conditions of the profile, the cost of the special joints to be installed between the sections

and the cost of the cable as a function of its diameter, the best possible subdivision of both the New York and Chicago lines was obtained. It is evident that a difference in cost of the special joint between sections of the feeding reservoirs or of the installation methods may lead to a different subdivision of the same line.

Each standard section of the line consists essentially, as shown in Fig. 6, of two stop joints which close the central oil passage in such a way that the oil of one section has no connection with the oil of the next section, of one set of feeding tanks which gives oil to the cables, and, in certain special conditions, of a pressure tank which supplements the oil supply to the cable.

Cable design. The cable installed in New York and Chicago is shown in Fig. 7. The conductor is made up of two layers of copper wires each 103.5 mils, (2.6 mm.,) in diameter stranded over a spiral of hard-drawn copper tape, specially shaped, see Fig. 5, so as to reduce the friction of the oil, as previously explained. The clear diameter inside the spiral is 0.75 in., (19 mm.,) and inside the first layer of copper wires is 0.85 in., (21.5 mm.). To

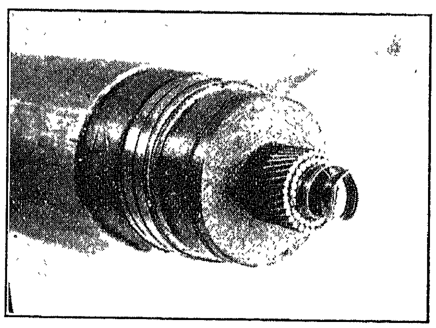

FIG. 7—ILLUSTRATION OF 132-KV. CABLE

facilitate the passage of oil between the stranded wire, from the central passage to the insulation special stranding was used. The outside diameter of the copper is 1.22 in., (31 mm.) The insulation thickness is 23/32 in., (18.3 mm.,) made up of wood pulp paper in three different gradations, depending upon the porosity. A mineral oil a little more viscous than that used in transformers is used for impregnating the cable.

After the impregnation at the factory and the electrical tests, the oil inside the central passage was removed before sealing the cable ends. The reason for this was to avoid the possibility of temperature variations during shipping, causing deformation of the lead sheath. The cable, as described later, was reimpregnated in the field after installation. Immediately after the high-voltage test and before removing the oil, an ionization test, difference between power factors at 20,000 and 95,000 volts, was made in the usual manner and also a special test, to determine the quantity of free gas inside the cable. This test, called an impregnation test, will be described later. After this test, a reinforcing armor made from a hard-drawn copper tape was wrapped over the first sheath lead between two layers of impregnated paper. Over this armor a second lead sheath was applied to protect the copper tape against the chemical action of the ground and to give a smooth surface while pulling into the ducts. It was necessary to use this reinforcement because the cable during operation is continuously subjected to the hydrostatic presure, as high as 105 ft. (32 m.) of oil, and this pressure may increase considerably when sudden loads are applied.

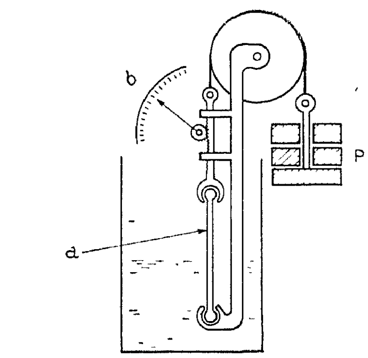

FIG. 8—LEAD TESTING MACHINE

A plain lead sheath would not have been able to withstand such pressure, even if its thickness was very great. Lead has more the characteristics of a liquid of extremely high viscosity than of a metal, and is deformed under the slightest stress. In this connection, the results of some tests made in Milan are quite interesting.

A sample of lead *a*, see Fig. 8, was subjected to a certain tension given by a weight *p* while immersed in an oil bath at constant temperatures, the index giving the elongation.

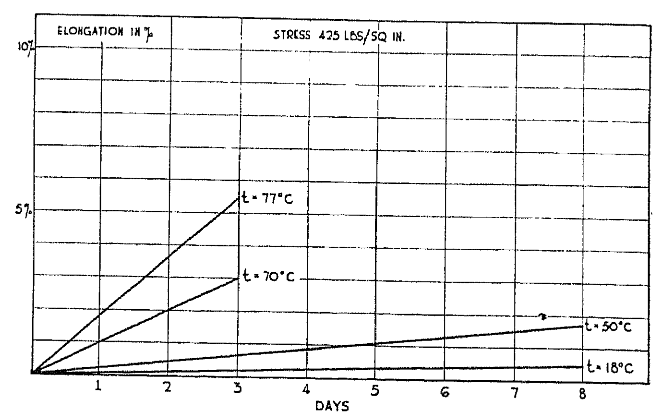

FIG. 9—ELONGATION CURVES OF COMMERCIAL LEAD

Several tests at different temperatures and with different weights were made for different qualities of lead and for the alloys generally used in cables, (tin or antimony) showing that, as a rule, the lead keeps on elongating in a more or less regular way up to the breaking point, while for very small loads and low temperatures, the deformation stops after a short time.

The speed of deformation increases rapidly with the temperature as shown in Fig. 9 which gives some of the results obtained.

Impregnation Test. One end of the cable being sealed, see Fig. 10, the other end was connected through a valve a to an oil reservoir at a higher level than the cable; at this same end a mercury manometer was provided and a valve b through which a certain quantity of oil could be drained from the system. If the valve a

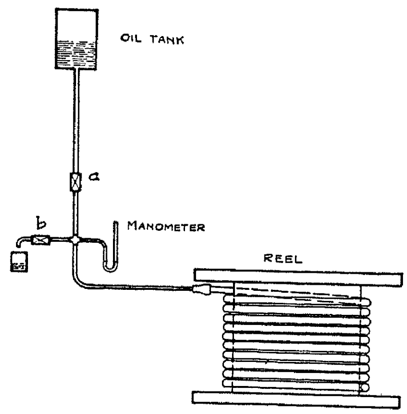

FIG. 10—METHOD OF MAKING IMPREGNATION TEST ON REELED CABLE

is shut, the manometer still indicates the pressure corresponding to the head of oil of the reservoir over the mercury level, but if the lead tube is not elastically deformed by the pressure and no free gas is occluded in the cable, no oil should come out when opening the valve b. Not taking into account for a moment the elasticity of the lead tube, it is evident that if a bubble of gas of volume v at a pressure p exists in a point of the cable, it will expand when opening the valve b, and assume, in a certain length of time, the volume $v + \Delta v$. A volume Δv of oil will come out from the valve b and the pressure of the gas bubble will drop to a value $p - \Delta p$.

If we take into account very small variations, we may consider Δv and Δp as differentials and starting from the characteristic equation of gases,

$$p\,v = \text{constant}$$

by differentiating, we have

$$d\,v = -\,d\,p\,\frac{v}{p}$$

What was said for a gas bubble may be repeated for all the bubbles existing in the cable and

$$\Sigma\,d\,v = -\,\Sigma\,d\,p\,\frac{v}{p}$$

But the sum of all the $d\,v$ is the total amount of oil drained from the valve b; calling it Δv and considering that Δp is the same for every point of the cable and can be read on the manometer, we have

$$\Delta v = -\,\Delta p\,\Sigma\,\frac{v}{p}$$

If the pressure is the same for every point of the cable, the total volume of free gas in the cable can be calculated readily. This condition of equal pressure in every point can be realized practically at the factory by laying the reel on one of its flanges, as shown in Fig. 10, and using a pressure p high enough. A very important and interesting point came out from the comparison of this mechanical test and the electrical test in the fact that the part of power factor corresponding to the ionization is proportional to the volume of gas in the cable as measured. In Fig. 11 the values of the variation of the power factor between 20,000 volts and 95,000 volts are plotted against the ratio of the quantity of free gas in the cable, to the total volume of the dielectric, the oil pressure being between the limits of atmospheric and atmospheric plus one meter head of oil.

In the impregnation test taken in the field, it is not possible to consider the pressure of the gas the same in the various points of the cable, with the exception of flat sections. Only the total amount $\Sigma\,\frac{v}{p}$ can be known. Apparently this expression does not seem to mean very much, but when we consider that on one hand the part of power factor due to the ionization of the occluded gas is proportional to its volume, and on the other hand that this value becomes proportionately smaller as the pressure increases, we may conclude that the expression

$$\Sigma\,\frac{v}{p}$$

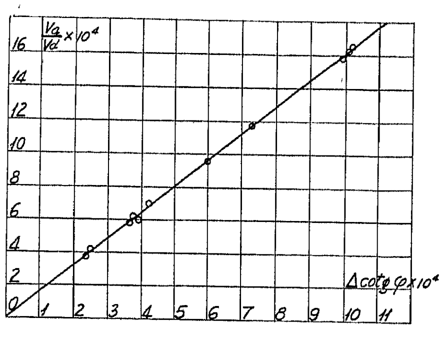

FIG. 11—RELATION-POWER FACTOR CHANGE TO ENTRAINED GAS

is a quantity which allows us to judge the electrical behavior of the cable. For this reason we have considered it as a measure of the impregnation of the cable.

It should be here noted that in the actual determination of $\Sigma\,\frac{v}{p}$ by test finite increments of pressure and volume are considered and these must accordingly

be kept small in order to avoid an appreciable error in the results.

When we started using this method in the field we met with the trouble that the oil pressure in the cable was not constant but changing from time to time due either to the variation of the temperature of the cable, or when the test was taken a few hours after impregnation, to the fact that the impregnation was not yet completed, especially in the joints. A method was made possible under these conditions in the following way: Let us suppose the pressure in a gas bubble of volume v be p, and p be a function of the time, t. At a certain moment we open a valve and let a certain volume of oil $d\,v$ flow out. The pressure which at that moment was p_1 drops down to $p_1 - d\,p_1$ and then continues to change according to a law similar to that of before. Let us suppose we know the mathematical connection between p and t

$$p = f\,(t\,a, b, c, \ldots.)$$

This includes certain constants $a, b, c, \ldots.$ depending upon the conditions of the cable. It is always possible to alter the same equation in such a way as to put in evidence beside or instead of some of the constants the value of p and v at a certain time t_1 say $p_1\,v_1$. The equation becomes

$$p = f\,(t_1\,p_1\,v_1 \ldots.)$$

It is now possible to take the differential of p in respect to p_1

$$d\,p = d\,p_1 \frac{d\,f\,(t_1\,p_1\,v_1 \ldots.)}{d\,p_1}$$

As we have to deal with gaseous bubbles, we can write

$$d\,p_1 = -\,d\,v_1 \frac{p_1}{v_1}$$

and then

$$\frac{v_1}{p_1}\,d\,p = -\,d\,v_1 \frac{d\,f\,(t_1\,p_1\,v_1 \ldots.)}{d\,p_1}$$

This gives the variation of p at any time in consequence of the variation $d\,v_1$ introduced at the time t_1.

If we write the same equation for all the bubbles in the cable and sum them, we obtain

$$d\,p \sum \frac{v_1}{p_1} = -\frac{d\,f\,(t_1\,p_1\,v_1 \ldots.)}{d\,p_1} \sum d\,v_1$$

which permits us to know at any time the variation of p due to the variation of $\Sigma\,v_1$ to $\Sigma\,v_1 + \Sigma\,d\,v_1$.

$\Sigma\,d\,v_1$ is the total amount of increase of volume of the gas bubbles at the time t_1 and can be produced by the subtraction from the cable of the same amount of oil. Let us call it $\Delta\,v_1$

At the time t_1 we have

$$\frac{d\,f\,(t,\,v_1,\,p_1 \ldots.)}{d\,p_1} = 1$$

$$\Delta\,v_1 = -\,\Delta\,p_1 \sum \frac{v_1}{p_1}.$$

The method is then as follows:

At the end of the cable, see Fig. 12, where the feeding tank is installed, a mercury manometer is connected. When the valve a is closed, it starts indicating the pressure in the cable. Let us take records of this pressure and plot the curve 1. At the time t, we open the valve b and let some oil out. We then close the valve and continue to read the pressure indicated by the manometer. The curve which would have been followed if no oil had been taken out is shown dotted. The true curve is shown a little lower and marked 2.

The first part of this curve between the times t_1 and t_2 is a transient and is due to the settling of the new conditions in the cable. It is not possible then to know $d\,p_1$ in any other way than prolonging the part

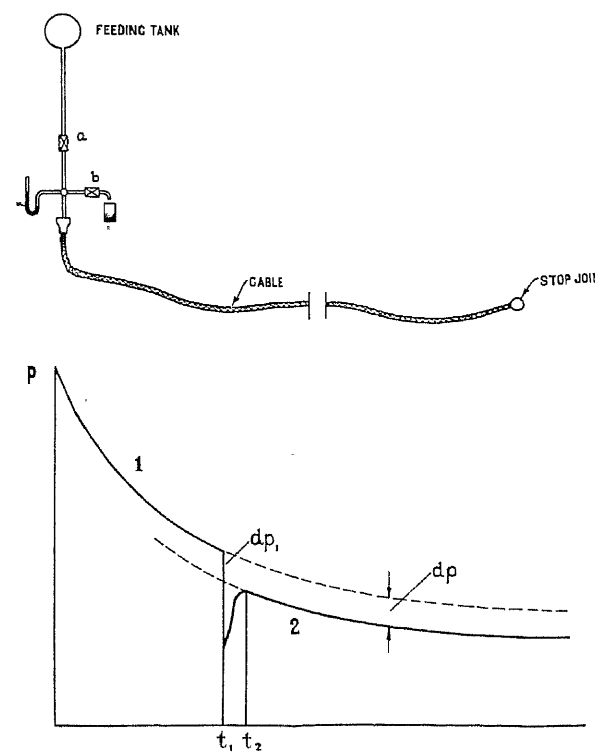

FIG. 12—METHOD OF MAKING IMPREGNATION TEST ON INSTALLED CABLE

considered as steady of the curve 2 to cut the ordinate p_1 as is shown by the dotted line.

We have then, easily, $\sum \frac{v_1}{p_1}$ from the formula.

$$\Delta\,v_1 = -\,\Delta\,p_1 \sum \frac{v_1}{p_1}$$

Of course, $\sum \frac{v_1}{p_1}$ corresponds to the pressure p_1 at the end of the cable and not to the pressure given by the feeding tank but in practise this difference can be kept very small.

A correction was introduced to take care of the

extension of the joints of the lead tube and of the pipes included in the system.

Description of the Special Accessories: Feeding Tanks. The principal requisites of the oil tanks are that the oil inside should always be practically at atmospheric pressure, independently of the volume of oil present in the tank, and that it should be in no way in contact with the surrounding air.

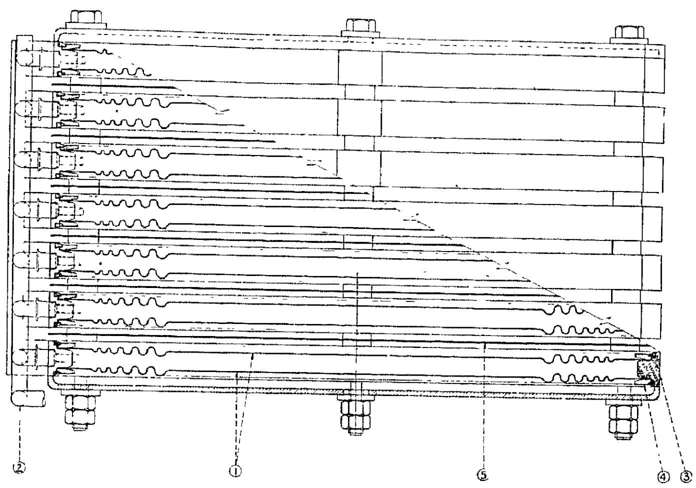

FIG. 13—FEEDING TANK

The problem has been solved using collapsible reservoirs made up with thin metal walls, which are easily deformable. In such a way the oil is not in contact with the air and yet acts with regard to the pressure as if it were contained in an open reservoir.

Fig. 13 gives the drawing of a feeding tank.

Seven separate cells, each with collapsible walls, *1*, are connected in parallel to a common manifold, *2*. Each cell is made up from a ring, *3*, on which two corrugated diaphragms, *1*, are soldered and kept in place by a ring, *4*. The corrugation allows the plates to move under expansion or contraction.

Two standard types of tanks were adopted, one with seven cells, as given in Fig. 13, called *S*-7, and one with 11 cells called *S*-11.

Each cable of a section was fed by two or more of these tanks, paralleled by means of valves and manifolds. Fig. 14 gives the value of the pressure of the oil inside *one* cell of a feeding tank, against the volume of oil in it, the pressure being given in centimeters of head of oil referred to the center of the tank, and the volumes in liters.

The area included in the curve is due to the hysteresis of the metal walls when deformed. See Fig. 14.

Pressure Tanks. As said before, the characteristic of this type of tank, Fig. 15, is to have a certain number of collapsible air-tight cells, *3*, full of gas, separated by heavy plates, *5*, contained in the tank, *2*, which is filled up with oil. The outside tank, *1*, is able to withstand the maximum pressures given by the oil of the section during expansion.

Each cell is perfectly tight and is filled with an inert gas, *6*, especially selected for the purpose.

Three standard types were adopted: *A*23 with 23 cells, as shown in Fig. 15, *A*17 with 17 cells, and *A*6 with 6. The curve of Fig. 16 shows how the pressure inside the tank varies as a function of the volume of oil given out by the tank, for a pressure tank of the type *A*6, pressures being expressed in Kg/cm^2. above atmospheric, volumes in liters.

Stop-Joints. As has been explained in the design of the cable, each section is connected electrically to the next one by means of a special joint, called stop-joint, which cuts the oil communication between them. See Fig. 17. The stop-joint consists essentially of a cylindrical tank, *1*, full of oil, *2*, which contains two inserted porcelain terminals, *3*, in a *V* arrangement.

The end cables of each section terminate in these potheads which are electrically connected at the lower part. As for the pressure tanks, the outer tank is of suitable thickness and has a lining, *5*, hermetically sealed to the upper cover, *6*. The terminal's insulators are cemented at the upper end to the cover and are provided at the lower part with two cemented metal caps, *7*; the tightness of the seams is guaranteed by composition cork gaskets.

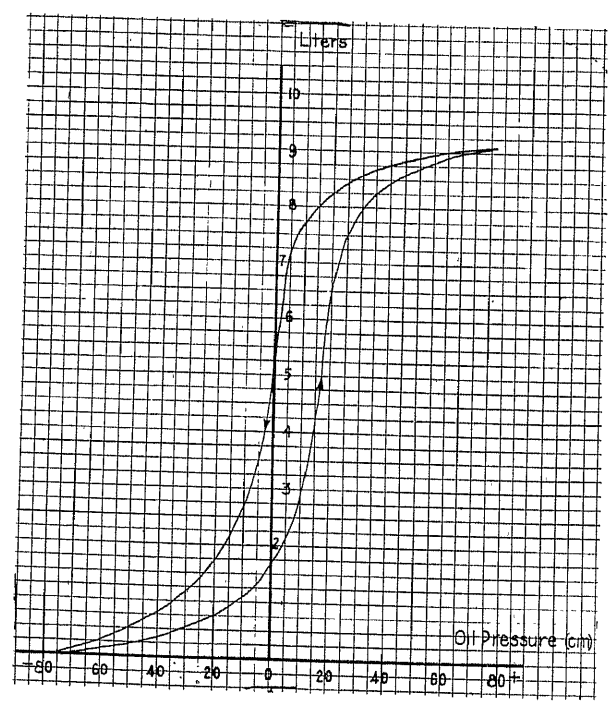

FIG. 14—PRESSURE-VOLUME RELATION OF FEEDING TANKS

The two caps are electrically connected by a flexible connection, *4*, and carry in the inside a set of brushes, *8*, for the contact with the connector, *9*, which is soldered at the end of the cables. The two lower caps and the connection, *4*, are screened by a metal box, *11*, so as to have a good distribution of the electric field; for the same reason the insulators are provided at the upper

end with electrostatic controls, *12*. The metal screen, *11*, is reinforced electrically with paper wrappings, *18*, and the discharge path to the case is protected by insulating barriers, *19*. The two end cables after being reinforced in the field with paper wrappings, *10*, and

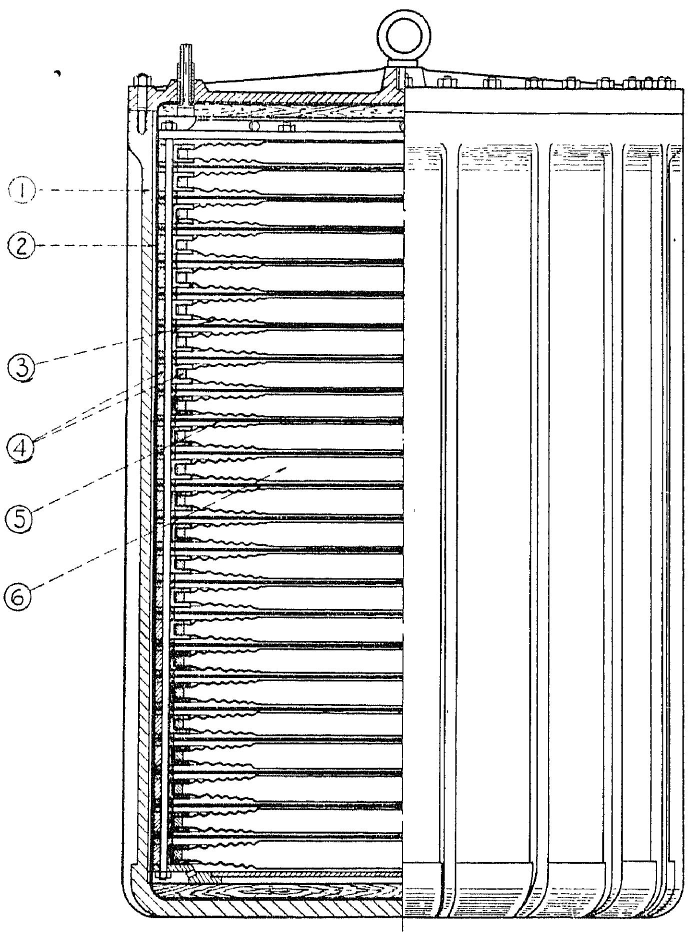

Fig. 15—Pressure Tank

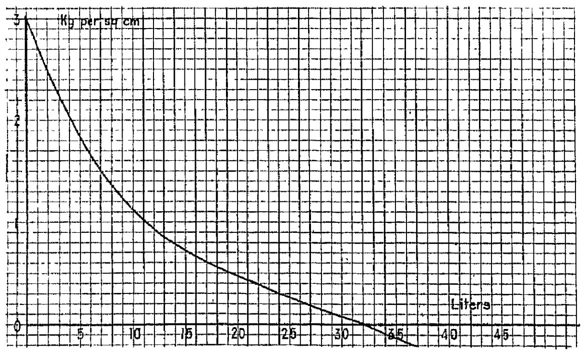

Fig. 16—Pressure-Volume Relation of Pressure Tanks

provided with electrostatic controls, *13*, are slipped inside the insulators so that their connector, *9*, is wedged between the brushes, *8*, and the lead sheath of the cable is soldered to the cover, by means of metal sleeves, *14*. As a matter of fact, the stop-joint tank is *raised* from a pit in the manhole up to its final position so that the cables slip inside the insulators. The only wipes to be made in the field are those at *15*. The oil is fed to the cables through a pipe, *16*, which is connected to the reservoirs at the feeding end of the section.

The oil chamber, *2*, inside the stop-joint is connected in the field through the pipe, *17*, to the terminal at the higher pressure, each terminal being at the pressure given by the height of the reservoir of the section to

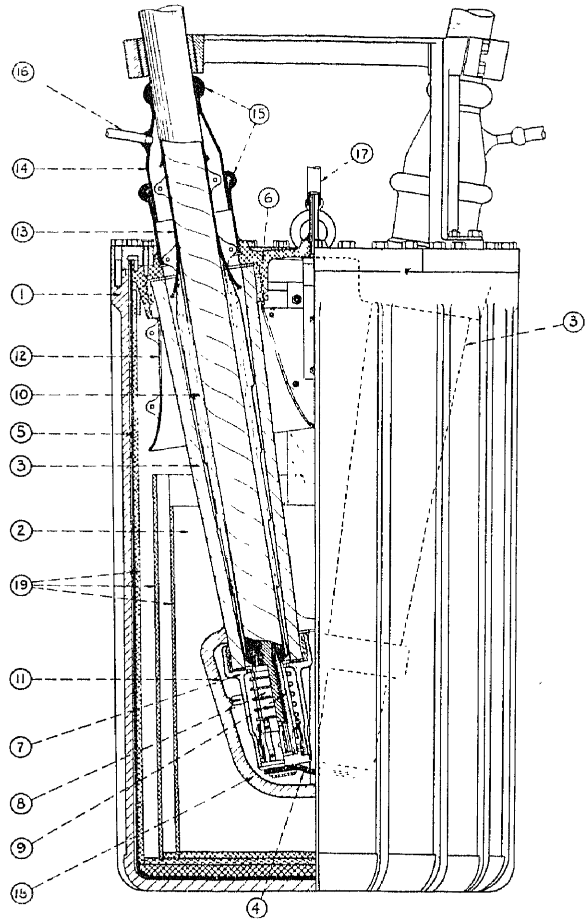

Fig. 17—Stop-Joint

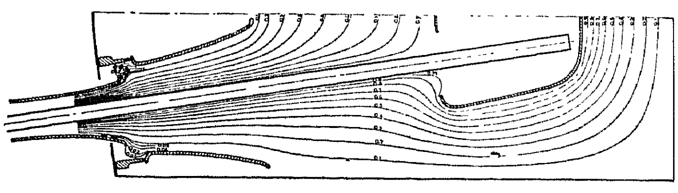

Fig. 18—Electrostatic Stress in Stop Joint

which it is connected. In this way, the oil in the tank is always at the same or at a higher pressure than the oil inside each of the insulators and the porcelain is subjected only to compression.

The distribution of the electrostatic field inside the stop-joint has been studied in the laboratory in an experimental way, plotting point by point the equipotential lines of a special model with the well-known electrolytic method, and is given in Fig. 18. The equi-

potential lines are taken on a section passing through the insulator's axis.

Terminals. Fig. 19 gives the drawing of a Pirelli pothead. This is essentially the same as the type developed by the General Electric Co. for this purpose, shown in Fig. 20. The upper connection, *1*, is provided with suitable openings, *2*, for the oil passage and the bottom connections, *3*, are provided for the oil pipes to the reservoirs. One of the

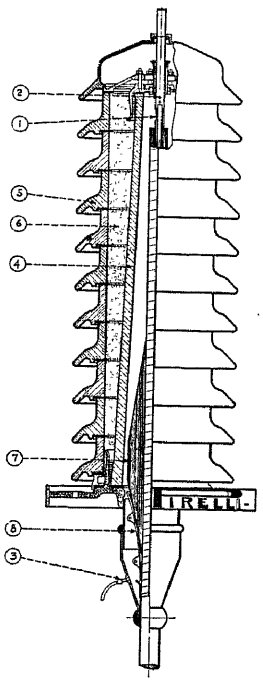

Fig. 19—Pirelli Terminal

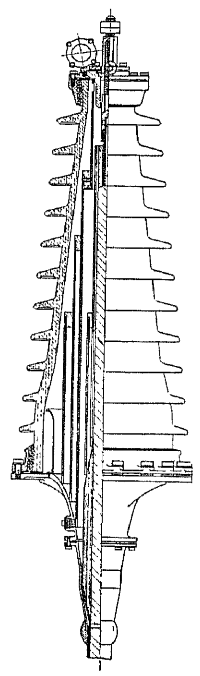

Fig. 20—General Electric Terminal

outstanding features of the Pirelli terminal is that it is made up with two porcelain insulators, a plain one inside, *4*, which guarantees the oil tightness of the system, and one outside, *5*, made up of several elements with petticoats which provide a long longitudinal path for surface leakage. The space between the two insulators is filled with compound, *6*, which acts as an elastic cushion against mechanical strains to the inside insulator.

In both types of pothead the cables are reinforced with insulation wrappings, *7*, and the stresses relieved with electrostatic controls, *8*.

Impregnation of the Cable in the Field. The installation and the following impregnation of the cable in the field were most delicate operations. This second impregnation was considered necessary so as not to trap air at the jointing points, and also, if the cable had been shipped and installed with the core full of oil, some of it would certainly have drained out during the splicing, especially due to the fact that the majority of the lengths were not laid level.

The operation was carried on in the following way: All the lengths of a section were spliced together and the end stop-joints, or terminals, of the section were installed. A certain number of joints along the section were not made up in the final way, but were built in a provisional way, as shown in Fig. 21, so as to permit the evacuation of the cable, not only from the true ends, at the stop-joints, but also at intermediate points of the section.

As a matter of fact, on account of the central passage not being perfectly free of oil, due largely to seepage from the paper during evacuation, oil slugs are formed all along the cable.

A drop in pressure is created across each slug and causes the vacuum in the core to become gradually worse, the longer the columns of oil in the slugs and the greater their number. A theory was developed which enables us to determine, graphically, exactly what these differences of pressure are in accordance with the profile of the section and also a method to check in the field the results of the calculations. We

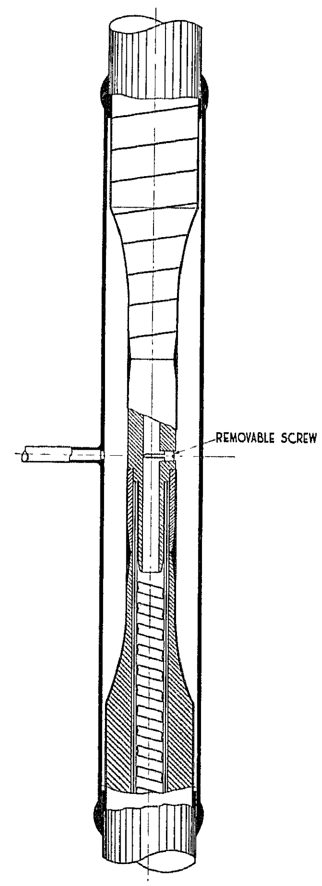

Fig. 21—Provisional Joint

can in this way calculate the distances between the provisional joints so that vacuum not poorer than a predetermined value will be developed, and this can be checked in the field.

In addition to this, a special impregnating process was developed which gives perfect results even if the vacuum reached in some point of the cable is not the maximum obtainable with the pumps. This re-impregnation in the field involves only a small portion

of the cable, probably only the central hollow passage and an adjacent thin layer of the insulation. Under such conditions, the gas occlusions which may remain in the core during this second evacuation are only a small percentage of this volume and therefore a minimum portion of the total volume of the cable. The vacuum, as said before, was applied at the stop-joints and at the provisional joints. After a certain number of hours, the impregnation was started by admitting oil into the core at the point where the feeding tanks are connected. The vacuum pumps at each provisional joint manhole were stopped after the oil had arrived at this location on all three conductors and had been carefully tested.

The impregnation of the cable was practically ended with the arrival of the oil at the stop-joint at the far end of the section and after the insulation and the joint had ceased absorbing oil.

After this an impregnation test as described was made; such a test, as a matter of fact, was studied especially to determine the impregnation quality, after installation, as it is not possible or at least not practical to take electrical measurements of it in the field.

The impregnation results obtained on the cable installed were of the same order as those on the reels after the impregnation in the factory.

When the impregnation was completed, the section was connected permanently to its feeding reservoirs. Before putting the cable in operation, the entire line was heated to full-load temperature several times by circulating current in the copper, in order to check the behavior of the various accessories, the oil flows, and also to verify the fact that the amount of oil in the feeding tanks was exactly the quantity required in accordance with the load and seasonal temperature variations.

This heating process was also used in some special instances to decrease the viscosity of oil and accelerate its flow during impregnation, when the weather was rather cold.

Incidentally, one of the advantages of this type of cable is that if any leak exists in the joint wipes or other connections, it will be immediately detected during evacuation, or if of later development, by the application of the oil pressure. In the usual type of cable, similar leaks, especially in those parts of the line which are completely under water, would allow the entrance of moisture, resulting sooner or later in the failure of the cable without preliminary indication.

Manufacture, Inspection, and Testing of the 132,000-Volt Cable

BY WALLACE S. CLARK[3]

Associate, A. I. E. E.

There are certain novel features in the manufacture of the cable which are, we hope, of sufficient general interest to warrant their introduction here.

3. General Electric Company.

In order to secure a central passageway through the conductor, a spiral of hard-drawn copper strip was formed and the wires composing the conductor proper were stranded around this. Special machinery was installed to make this spiral and special precautions had to be taken in stranding the individual wires around it, the inner layer of wires being dented to give free circulation of oil.

The wood pulp paper used in forming the insulation wall was of three different thicknesses and varied in density, the thinnest and most dense paper being put next to the conductor where the electrical strains are greatest, then the intermediate paper, and on the outside the least dense and thickest paper.

After the core was completed, a radical departure from ordinary practise occurred. The insulated core had the first lead sheath applied, was wound on a reel and heated by immersing it in a steam bath. The ends of the cable were sealed and insulated leads were brought out through these seals.

The exhaustion of the heated cable core with vacuum pumps was the next step.

Measurements were taken periodically of the power factor of the cable and the insulation resistance between the conductor and the lead sheath during the evacuation. The particularly interesting point in this process is that if the lead sheath has any imperfections in it, moisture (steam) will naturally be sucked in through these imperfections and the electrical measurements made will indicate that this is happening. This makes it improbable that there should be undetected faults, such as porous spots or pin-holes in the lead.

When the desired electrical measurements were obtained, oil, which previously had been given a special treatment for purification and for the removal of all absorbed gases (ordinary transformer oil will absorb from 15 to 20 per cent of its own volume of air), was admitted to the central core very slowly, saturating the paper wall.

The cable was finally cooled down under oil pressure and when room temperature was reached, it was taken from the tank and was ready to test.

After testing, the ends were hermetically sealed and the cable was then ready to receive its armor and outer jacket of lead.

The armoring consisted of wrapping the inner lead sheath with treated paper tape; next with a thin hard-drawn copper tape; then a second paper tape. The cable was then taken back to the lead press and leaded over all, and was made ready for shipment on especially large bodied reels, after removal of the oil.

Tests. The specified tests were similar to those of the A. E. I. C. Specifications, and the principal ones were as follows:

a. Each reel of cable had to stand 175,000-volt alternating current for 15 min. between conductor and sheath.

b. Samples maintained at 0 deg. cent., freezing, for

two hours were bent three cycles to 180 deg. around a drum having a diameter 15 times the diameter of the cable, and then withstood 225,000-volt alternating current for five minutes.

c. One full reel of cable from each 15,000-ft. lot was tested with 140,000-volt alternating current for eight hours.

d. The original specifications called for a test after installation of 140,000-volt alternating current for 15 min. between conductor and sheath. As it was impractical to secure transformers for this, special kenotron testing sets were provided in New York and Chicago, and the cable successfully tested with 300,000-volt direct current for 15 min.

The maximum power factor on any one section of cable at room temperature did not exceed ½ of 1 per cent, and the power factor at 65 deg. cent., maximum operating temperature, did not exceed 0.65 per cent. The difference in power factors, ionization, when measured at stresses of 20,000 and 95,000 volts, 28 and 132 volts per mil, respectively, did not exceed 0.2 per cent. The average figures were very much better than these.

In connection with the ultimate breakdown tests, which were performed on these samples after they had passed all the required voltage tests, it is interesting to note that comparing the breakdown tests with those made on General Electric cables of standard type without oil ducts and intended for maximum working pressure of 75,000 volts, and having only 1/64-in. thicker insulation, the short time breakdown voltages were about the same; but with long time tests at lower voltages, the oil-filled cable far out-distanced the ordinary type.

Special Tests. Samples of cable were run 24 hr. at 225,000-volt alternating current without breakdown or injury. This was three times the working stress.

The five-min. breakdown on samples was about 400,000 and the one-hr. breakdown about 300,000-volt alternating current.

One special test at Milan ran 30 hr. at 200,000-volt, after which the potential was raised to 260,000-volt alternating current and held for 20 hr. without failure.

A very interesting feature shown by the special tests was that a length of cable could be tested and the constants determined; then, after a heating and cooling cycle, be remeasured substantially without change in the results. This is one of the best guarantees of minimum electrical deterioration which can be determined by test.

The general results at Milan and Schenectady showed good agreement, even though some of the Milan tests were made at 42 cycles instead of 60 cycles, and all tests exceeded the specifications by a large margin.

Duplication of manufacturing processes at Schenectady and Milan was secured through the freely offered assistance of the Pirelli engineers and the constant interchange of manufacturing data.

Inspection. All cable manufactured for the New York Edison and United Companies, both at Milan and Schenectady, was inspected as to processes and all tests witnessed by the Electrical Testing Laboratories, which maintained a resident inspector at the Pirelli factory in Milan for about nine months, especially for this purpose. Cable for the Commonwealth Edison Company, manufactured at Schenectady, was also inspected by the Electrical Testing Laboratories while that manufactured at Milan was inspected by Messrs. Guido & Marco Semenza, representatives of Merz & McLellan, Consulting Engineers, of London.

Installation of the 132,000-Volt Cable

By A. H. Kehoe[4], Fellow, A. I. E. E.
C. H. Shaw[5], Associate, A. I. E. E.
J. B. Noe[5], and Associate, A. I. E. E.
D. W. Roper[6]. Fellow, A. I. E. E.

Location and Description of Route. In New York the cable runs from the Hell Gate Generating Station of The Edison-United Companies, northward through the

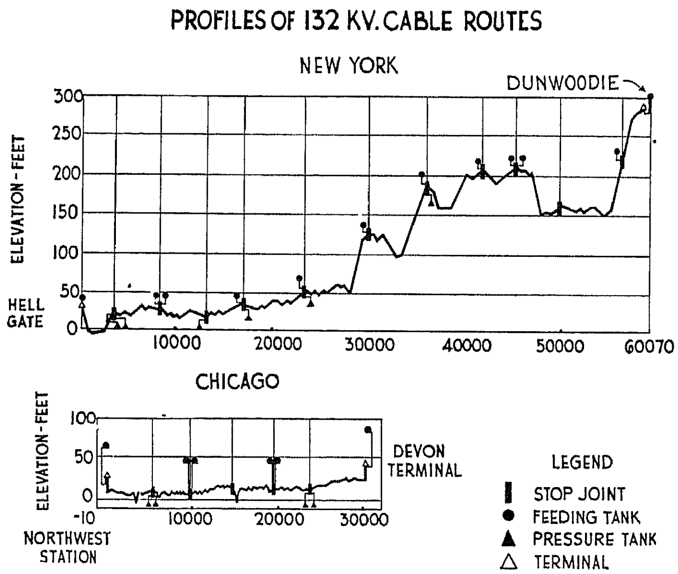

Fig. 22—Profiles of 132-Kv. Cable Route

Borough of Bronx and up to the Dunwoodie Distributing Station, in the city of Yonkers, Westchester County, a total distance of about 12 mi. The feeder will be used to supply the rapidly growing area of Westchester County, immediately north of New York City, having in mind also the possibility of its use in the future as a link in the supply of water power from the St. Lawrence district directly into the metropolitan area of New York.

In Chicago, the 132,000-volt feeder runs from the Northwest Generating Station of the Commonwealth Edison Company northward to the city line, a distance of about six mi., where it is connected to 30 mi. of overhead line, continuing northward to the Waukegan Station of the Public Service Company of Northern

4. United Electric Light & Power Company.
5. The New York Edison Company.
6. Commonwealth Edison Company.

Illinois. The line thus serves as a tie between generating stations, and transmits power in either direction, as may be required. As may be seen from the line profiles in Fig. 22, there is a difference in level of 285 ft. between the high and low points in New York, compared with 27 ft. in Chicago, excluding the river crossing. This difference in topography and grades made necessary radical differences in sectionalizing the line and the location and operation of the tanks supplying oil to the cable.

Figs. 23A and 23B show diagrammatically the connections of the New York and of the Chicago lines. Fig. 24 shows the initial transformer installation of 30,000-kv-a. capacity at Hell Gate. The initial installation at Chicago was 45,000 kv-a. In each location, provision is made for additional units to bring the transformer capacity up to the full line capacity of 90,000 kv-a.

In New York, the southerly half of the feeder cable was Pirelli make, the northerly half, General Electric. In Chicago, the cable for two phases was supplied by the General Electric Company, and that for the third, by Pirelli.

Conduit and Manhole Construction. In 1925, preliminary surveys were made in both New York and in Chicago to decide upon the best routes for the 132,000-volt lines. Profiles were prepared and the routes were finally decided upon after consultation between the engineers of the two operating companies and those of the Pirelli and General Electric Companies. In both cities, entirely new conduit lines were constructed for the high voltage feeder, with duct space provided for the installation of a second feeder.

Conduit Construction in New York. In New York the conduit is of monolithic concrete construction, using 4-in. ducts, with two inches of concrete separation. In the Yonkers portion there are nine ducts, arranged three by three, and in the Bronx portion 12 ducts, built in the form of an inverted "T". The maximum cable length is 400 ft. for straight sections, curved sections being shorter in proportion to their curvature. Fig. 25 shows plan and elevation of the standard manholes used in New York and in Chicago and the method of racking the cable. Note especially the racking in the Yonkers manholes, which keeps the cables in a horizontal plane, each with an offset consisting of two full 90-deg. bends with a minimum bending radius of 24 in., allowing easy expansion and contraction of the cable with a minimum strain on the splice.

L-shaped angle manholes are placed where the direction of the system changes. Fig. 26 shows a typical angle manhole as used in New York.

The special stop-joint manhole, Fig. 27, of which

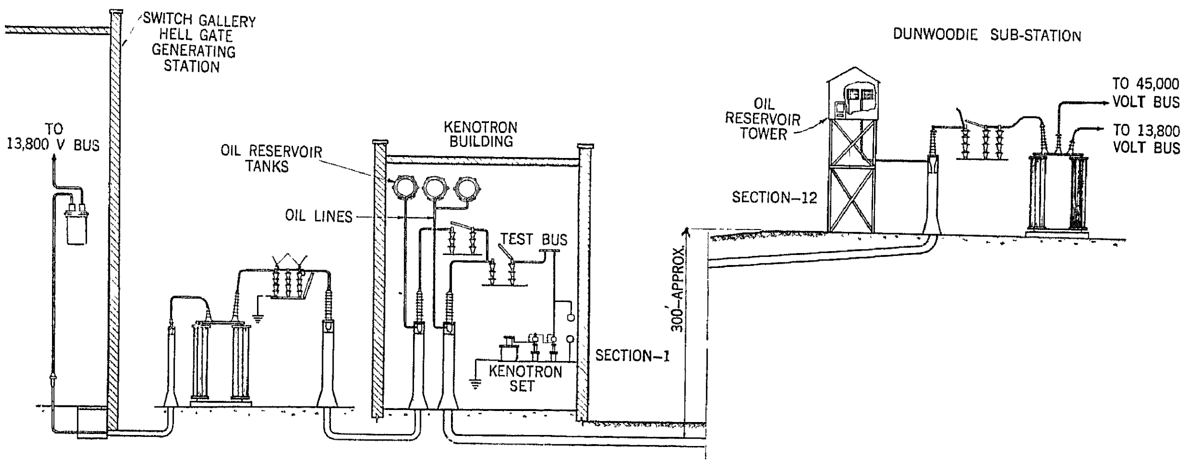

FIG. 23A—DIAGRAMMATICAL CONNECTIONS OF LINE—NEW YORK

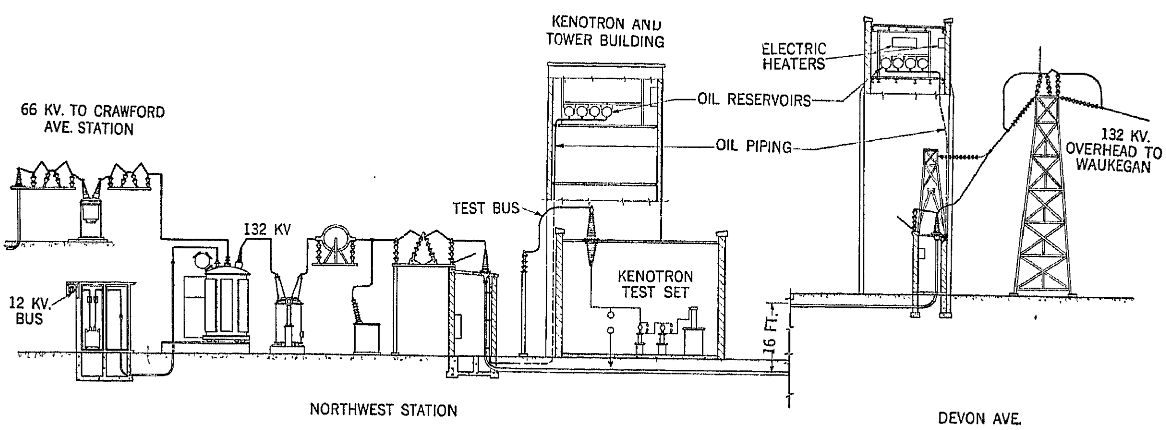

FIG. 23B—DIAGRAMMATICAL CONNECTIONS OF LINE—CHICAGO

there are 11 on the entire line, is 8 ft. wide, 12 ft. long, and 10 ft. deep, with a pit 4 ft. deep to allow for installing or replacing the stop joints. I-beams are built into the ceilings of these holes for lowering or raising the stop-joints. Normally the stop-joint tank rests on iron gratings placed over this pit, but these gratings can be removed when the joint is to be lowered.

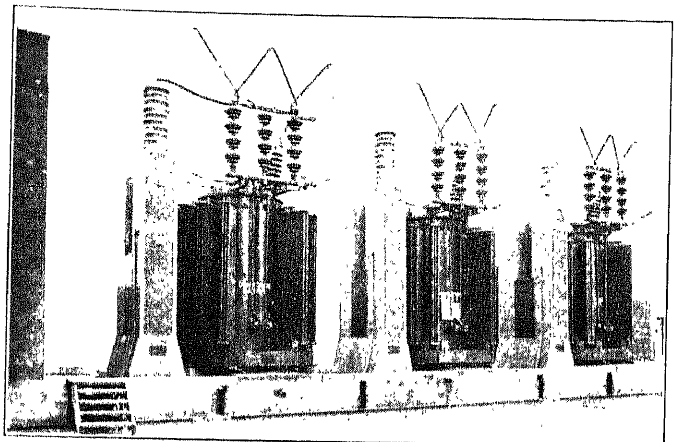

Fig. 24—Initial Transformer Installation at Hell Gate

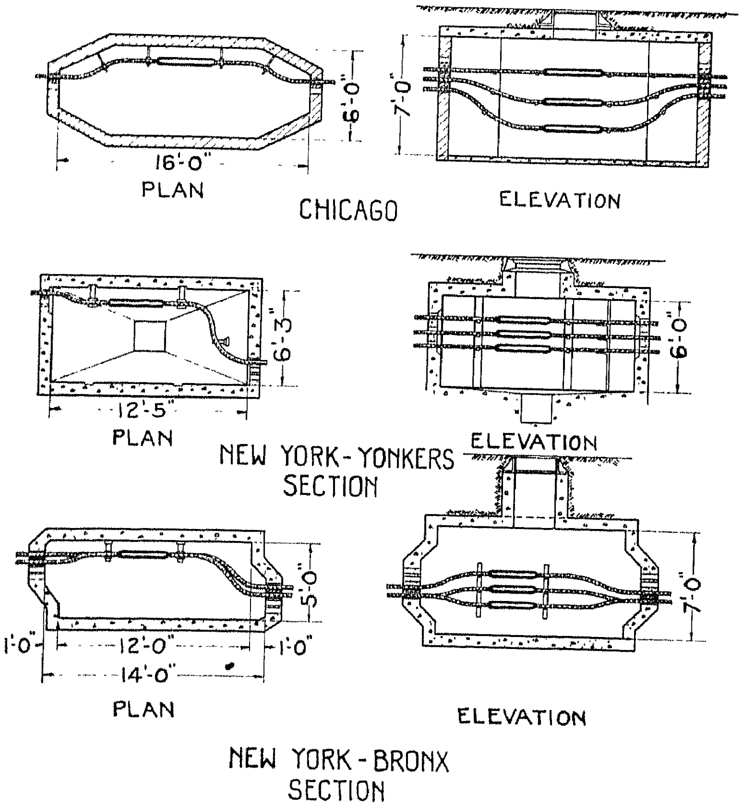

Fig. 25—Standard Manholes—New York & Chicago

In connection with the stop-joint manholes, reservoir manholes, Fig. 28, were constructed for the installation of the reservoir feeding tanks. These were located at a sufficient elevation from the stop-joint manhole to give the proper head of oil for feeding into the cable sections. I-beams were built into the ceilings of these holes for supporting the tanks. At three locations it was necessary to build special structures for containing the reservoir tanks, namely, at the Hell Gate Station, where the tanks are contained in a portion of the Kenetron Building, at the Yonkers city line, where a small house of a bungalow type was built, and at Dunwoodie Station where a tower was constructed.

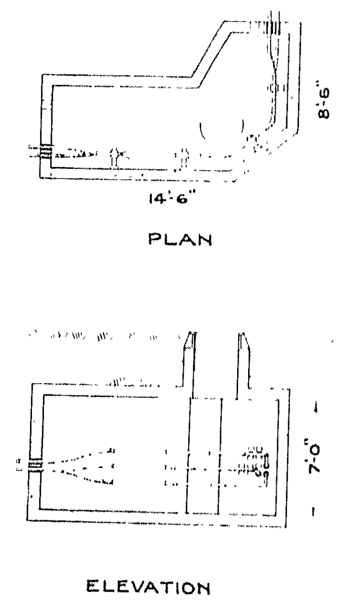

Fig. 26—Typical Angle Manholes New York

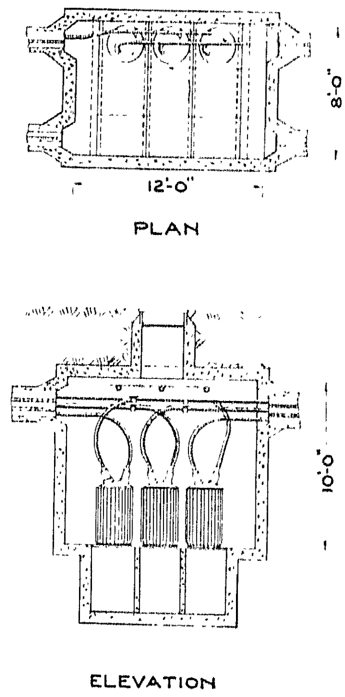

Fig. 27—Typical Manhole for Stop Joint

Conduit Construction in Chicago. The internal diameter of the ducts was four in. and the conduit structure consisted of eight ordinary precast concrete ducts, such as have been used previously in Chicago, laid in a two wide by four high formation. In order to avoid

having any high points in the cable, the ducts were installed in a straight line between manholes wherever possible; otherwise the conduit was installed in one long radius bend, concave upward. The maximum distance between manholes was made about 500 ft. in order to prevent excessive strain on the cable during installation.

The manholes for permanent joints are 50 to 100 per cent larger than manholes used in the past, and were designed to accommodate a joint 5 ft. long and to permit training of the cable at radii of 30 in. or more.

The manholes for the stop-joints are 18 ft. long by 8 ft. wide by about 10 ft. deep and have a 4-ft. pit to facilitate the placing of the ends of the cable in the stop-joint tanks. Separate manholes are provided for the pressure tanks adjacent to the two end stop-joint holes.

installation was done under the direct supervision of the engineers of the manufacturers.

Due to the high voltage at which the cable is to be operated and to the hollow type of construction, extreme care was taken to ascertain that the ducts were of the proper size, entirely clean and free from obstructions before the cable was pulled. Special mandrels and brushes were pulled through each duct for this purpose, the cleaning being repeated, if necessary, until no more material was brought out. An elaborate series of pulling tests was made, using a continuous reading dynamometer rig, especially designed to determine the pulling tension. In these tests, grease and soapstone applied in various ways were thoroughly tested and their relative efficacy obtained, typical curves being shown in Fig. 30. The result was the adoption in both New York and Chicago of pulverized

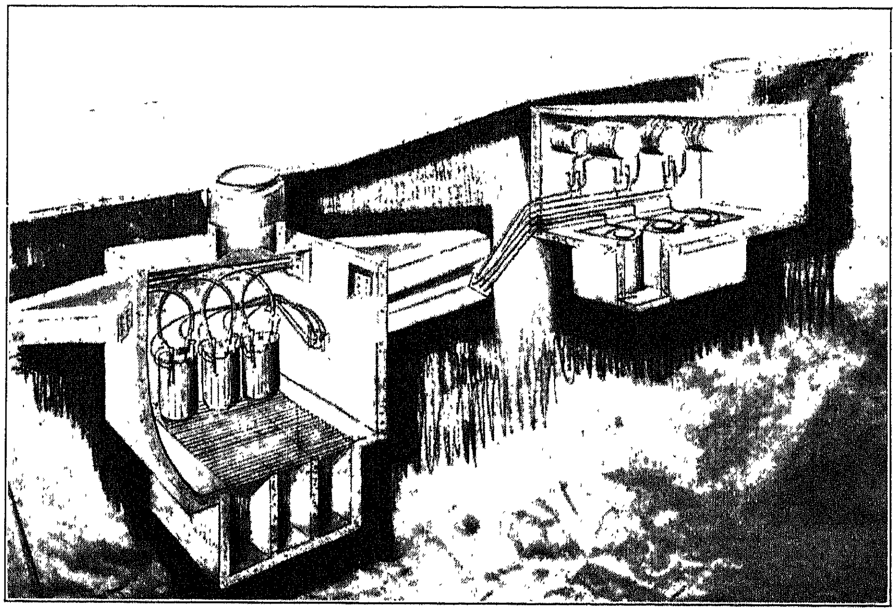

Fig. 28—Diagram of Reservoir Manhole Connections

Towers. In order that sufficient hydrostatic pressure might be maintained on the oil inside the cable, it was necessary that the feeding reservoirs be elevated above the section of the line being fed. In Chicago, where the ground contour was practically flat, this result was secured by placing the oil reservoirs in towers located at the ends of the line and at two intermediate points. In New York, it was possible by taking advantage of the hills to obtain sufficient pressure with the reservoirs located in manholes, except at the two terminals of the line. Figs. 29A, B, and C.

Cable Installation. On account of the radical differences between this cable and the types previously installed, and the fact that these were the first commercial installations of this new type of cable, many new problems were encountered during installation. In addition to the ordinary supervision by the forces of the operating companies, therefore, the entire work of

soapstone as a lubricant applied to the duct by the use of a series of flexible disks secured to a chain. The soapstone was inserted between the disks and deposited on the duct surface as the disks were drawn through the duct. As further precaution, some soapstone was added on the cable as it entered the duct.

In Chicago, about one-half of the cable route lay across open marshy country where the streets had not yet been cut through. This introduced serious problems in the transportation of the heavy reels and voluminous auxiliary apparatus, as well as the actual pulling of the cable, all of which difficulties were successfully overcome by the use of caterpillar tractors, trailers, and mud sleds; see Fig. 31.

Specially designed pulling eyes were installed on the cable by the manufacturers so as to prevent collapse of the central core during pulling and to keep the cable end completely sealed, Fig. 32.

In New York, during the pulling of the cable, thermocouples were wiped on to the lead sheath and pulled into the duct with the cable at six selected locations.

Complete records were kept of the pulling tensions obtained on every section, some average figures being:

Straight 400-ft. section, down hill. . 2400 lb.
Straight 400-ft. section, level. . . . . . 3500 lb.
Curved 300-ft. section, radius 500 ft. 4000 lb.
Average pulling tension. . . . . 9 lb. per ft.

Cable Splices. While the manufacture of the cable at Milan and at Schenectady was practically identical, the standard joints were radically different, each manufacturer supplying the jointing material to be used in splicing his own cable.

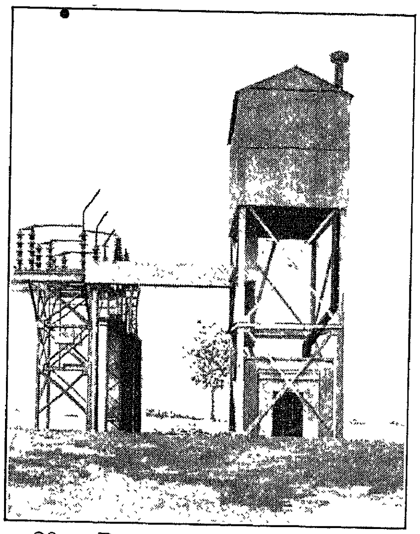

FIG. 29A—DUNWOODIE TERMINAL TOWER

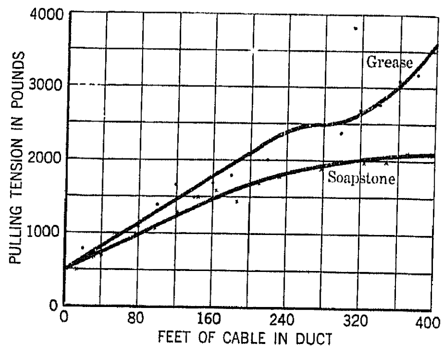

FIG. 30—CURVES OF RELATIVE PULLING TENSION—GREASE AND SOAPSTONE

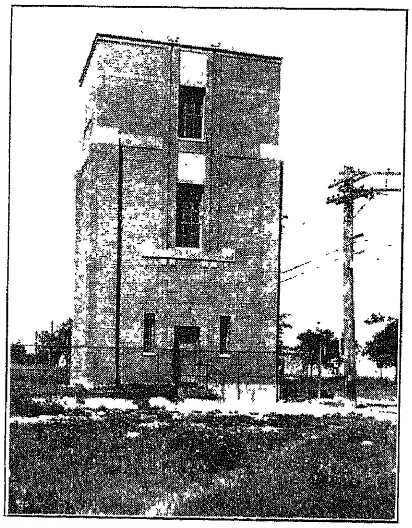

FIG. 29B—BRYN MAUR INTERMEDIATE TOWER—CHICAGO

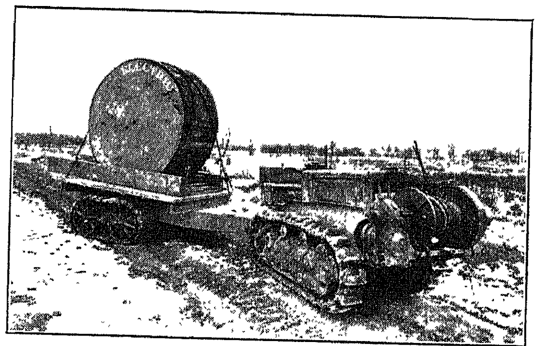

FIG. 31—CATERPILLAR TRACTOR

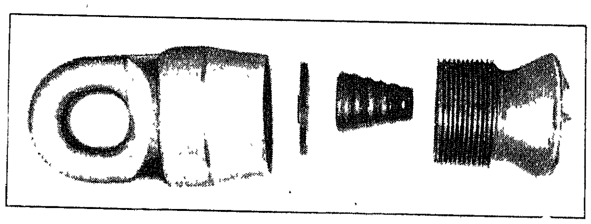

FIG. 32—PIRELLI PULLING EYE

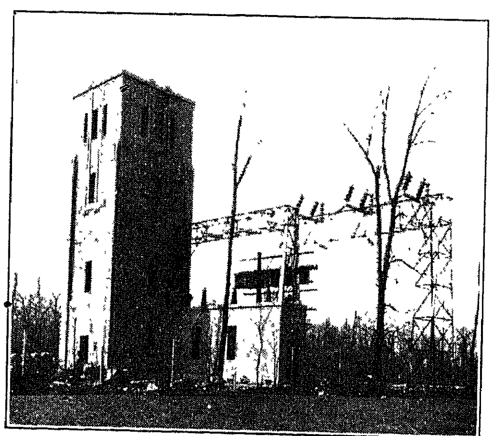

FIG. 29C—DEVON TERMINAL TOWER—CHICAGO

Pirelli Type. Fig. 33 illustrates the various stages in making, and the general design of the Pirelli joint.

The connectors for connecting the hollow core cable and continuing the passageway for oil in the center of the cable through the joint are similar in the Pirelli and General Electric joints. The connectors have in the center a transverse hole closed by a screw so that any joint, before it is insulated, can be arranged to communicate directly with the oil passage in the center of the cable.

The chief characteristic of the Pirelli joint is that the insulating material in the joint is paper which has been previously dried and prepared in the factory. This paper is not impregnated, but is surface-treated to reduce the absorption of moisture which might be collected during the process of jointing.

Another distinct feature is that the original insulation of the cable, after it has been properly penciled, is covered with a thin oil silk tape to reduce seepage of

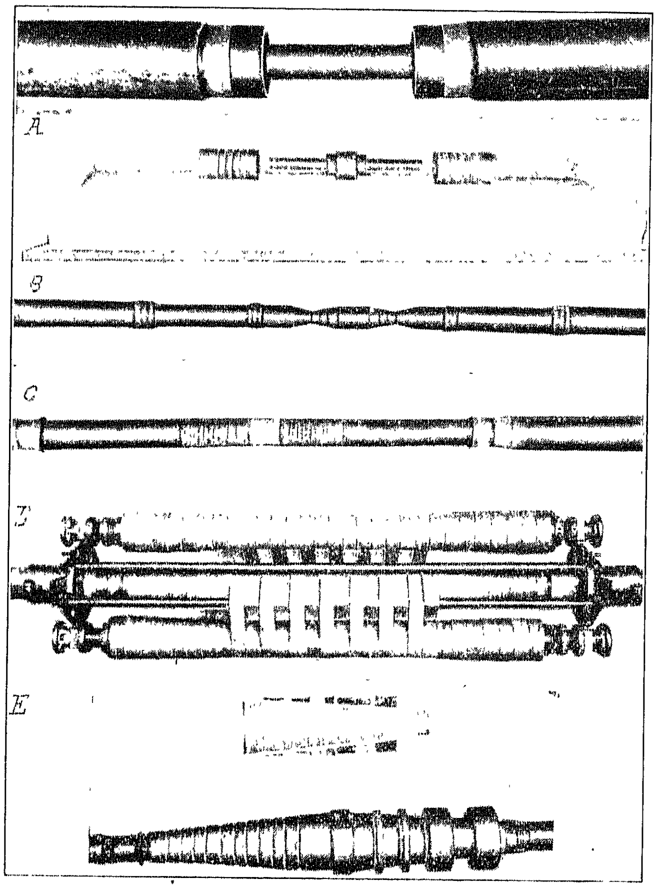

FIG. 33—PIRELLI JOINT CONSTRUCTION

oil between the joint insulation applied in the manhole and the original insulation in the cable proper, the object being to evacuate and impregnate the insulation of the completed joint independently of the cable insulation.

Fig. 33C shows the insulation brought up to the original diameter of the cable insulation.

Fig. 33D shows the machine application of the specially treated paper reinforcing the insulation already applied.

Fig. 33E shows the aluminum shields which are applied to the finished insulated joint before the lead sleeve is put on. These shields act as controls of electrical stresses and allow free access of the oil to the joint insulation and at the same time, support the lead sleeve against collapsing during vacuum treatment.

The outside sleeve is of lead, usually split longitudinally for convenience in applying over the aluminum forms shown in Fig. 33E. After this sleeve is wipe-jointed to the cable and the seam soldered, it is reinforced with exterior armor so that it may compare in strength with the armored cable sheath. The length of the joint is 44 in., (1120 mm.) and the diameter inside is 6.2 in., (156 mm).

The completed joints, as described elsewhere, are field impregnated. Prior to adoption, these joints were thoroughly tested out at Milan.

General Electric Type. Fig. 34 illustrates the General Electric type of joint which, it will be seen, differs radically from the Pirelli joint: First, in having the original cable insulation stepped as shown in Figs. 34B and 34C to secure longitudinal dielectric strength, and second, in being taped by hand with specially prepared varnished cambric which is packed under oil in sealed containers and which

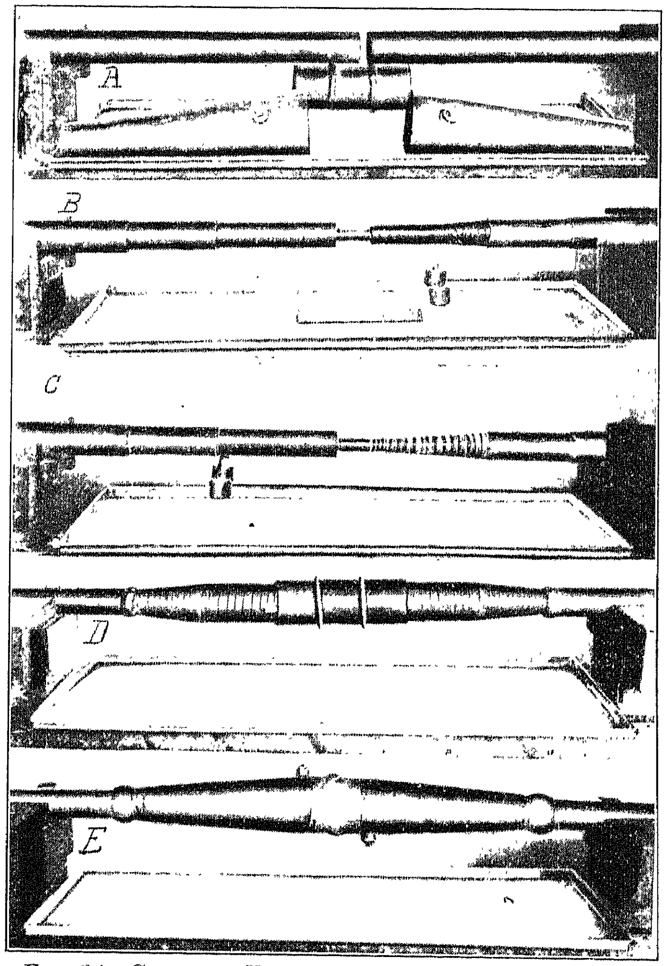

FIG. 34—GENERAL ELECTRIC JOINT CONSTRUCTION

is flushed with a special compound during taping. This insulation permits slow percolation of oil.

The joint is held concentric within the copper casing by the insulation cylinder and treated wooden wedges shown in Fig. 34.

The tapered ends of the insulation are wrapped with flexible copper tape which is united to the lead sheath of the cable, distributing the stresses at the ends of the

joint and preventing any stress coming on thin films of oil between the insulation wrapped on the cable and the outer casing.

The two parts of the copper casing which telescope are united to the cable and to each other by wiped joints. In cases where corrosion is feared, the exterior of the copper casing is tinned all over.

The casings are stiff enough to resist any tendency to collapse during the evacuation of the cable in the field and are stronger against bursting pressure than the lead sheath of the cable. No interior or exterior reinforcements, therefore, are required.

The principles of the insulation and stress distribution of the joint are the same as those of the General Electric 45,000- and 66,000-volt joints which have had thorough field trials in several installations.

Short and long time over-voltage tests on the General Electric 132,000-volt joint have shown it to exceed in strength the original cable insulation. The length of the joint is 42 in. (1073 mm.) and the diameter inside is six in. (153 mm.)

Before any joints were constructed in the field, the splicers, foremen, and engineers were given a very careful training in the details of construction at the shops of the operating company, under the direct supervision of the manufacturers' engineers. The New York company sent a special delegation of foremen and splicers to Pittsfield, where they were given instruction in the making of the General Electric joint.

The splicers were first given practise in making the essential parts of the joints on short pieces of cable and were then required to perform the more difficult operations in a manner acceptable to the supervising engineer and finally to make one or more complete joints.

One of the outstanding features in the construction of both the Pirelli and the General Electric joints was the care used to keep moisture out of the joint. To accomplish this, two small hot air electric blowers of the hand hair dryer type were arranged so as to direct a blast of hot air on the joint from the time the lead sheath was removed until the sleeve had been placed on the finished joint.

Each splicing gang was equipped with a dust ring which was put in place at the manhole before beginning work to keep street dust and dirt from blowing into the manhole during the making of the joint. Although joints were not started during the rain, it sometimes happened that it began to rain during the splicing operation, and for this reason each splicing gang was equipped with a tent which could quickly be placed in position over the manhole. Plastic roofing cement was also supplied with which the dust ring was set into the manhole in order to prevent water entering from the street.

Upon completion, each joint was tested for tightness by applying a pressure with carbon dioxide gas. A soap solution or a heavy oil was placed on the wipes to give an indication of any leaks or porosity. Some of the first wipes made were found to be porous, but after some experimenting it was discovered that by adding pure tin to the solder, and glazing over with a blow torch, tight wipes invariably resulted.

Two splicers were required in the manholes to build a joint. On the General Electric joint, the splicers performed the taping operation in relays, while on the Pirelli joint during taping, one splicer worked at each end. The time required to construct a permanent joint was about eight and ten hours for the General Electric and Pirelli joints, respectively. The time for making the provisional joints was about six hours.

Before splicing operations were started on either the Pirelli or General Electric cable, it was necessary to make special arrangements to provide energy for light and power, which was required along the line for making the joints and evacuating the cable. In Chicago the necessary power was readily obtained

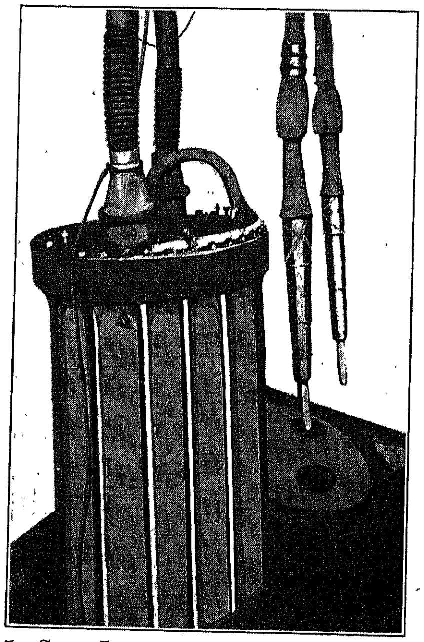

Fig. 35—Stop-Joint and Prepared Cable Ends

by the installation of service cables in the vacant ducts along the line, but in New York this was not feasible and it was necessary to use portable storage batteries and gasoline-engine-driven generating units.

Stop-Joint Installation. The stop-joint was first lowered into the pit in the floor of its manhole, after which the cable was carefully trained so as to leave the ends nearly perpendicular over the stop-joint cover. The ends of the cable were prepared as for an ordinary joint and the special contact terminals sweated to the two conductors. The protective caps were then removed from the porcelain tubes of the stop-joints and the stop-joints were lifted upwards into place, while the cable ends were slipped into the porcelains until they made contact with the spring terminals at the bottom of the porcelain tubes. The cable was then given its final training and wiped at the stop-joints.

The right hand portion of Fig. 35 shows a stop-joint lowered into its pit with the prepared cable ends in position just above it.

Special care was used in the stop-joint manholes to so train and secure the cables that any motion due to heating and cooling would not result in bending the lead sheath at the wipes at the top of the joint.

Installation of Feeding and Pressure Tanks. In order to avoid injury to the thin collapsible plates used in the feeding tanks, it was necessary to use great care in first lowering the tanks into the manholes and then raising them to hang from the I-beams in the roof.

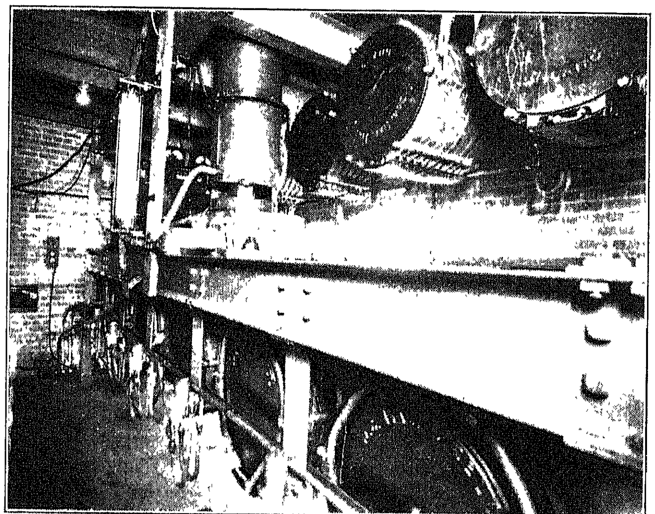

FIG. 36—FEEDING TANKS IN POSITION

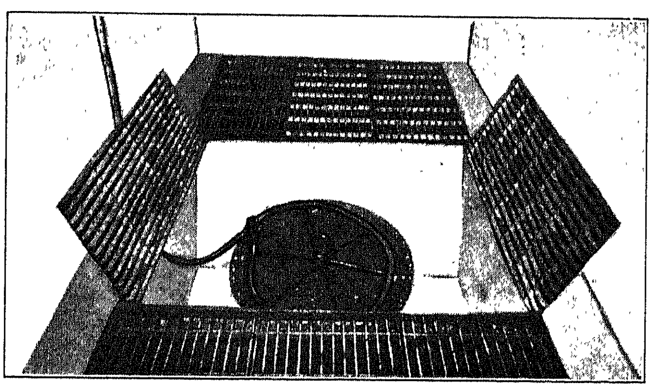

FIG. 37—PRESSURE TANKS IN POSITION

Fig. 36 shows an installation of feeding tanks in a tower.

The installation of the pressure tanks presented no particular difficulties; they were simply lowered into position in the bottom of the manhole; see Fig. 37.

A typical stop-joint installation, with feeding and pressure tanks and oil pipe lines, is shown diagramatically in Fig. 28.

Installation of Valves and Oil Lines. The oil lines used for the various connections between tanks and cable were of three different types; bare lead pipe which was used mainly for connections to joints and valves, jute-covered lead pipe which was used for connections between valves and feeding tanks, and steel wire armored lead pipe which was used where the oil line was pulled in ducts. A typical installation of oil pipe line and valves can be seen in Fig. 28.

Installation of Terminals. All of the Chicago terminals are of the General Electric type, but in New York, Pirelli terminals were used on Pirelli cable and General Electric terminals on General Electric cable. Drawings of the two types of terminals are shown in Figs. 19 and 20.

Oil Conditioning Equipment. The oil used in impregnating the cable and filling the hollow core, feeding reservoirs, pressure reservoirs, stop-joints, and terminals was the same as was used in the factory for the original cable impregnation. It was developed under the supervision of the Pirelli engineers to meet their especial requirements as to dielectric strength, viscosity and flow point. The oil used has a flow point of minus 15 deg. cent., or lower, which insures proper functioning of the

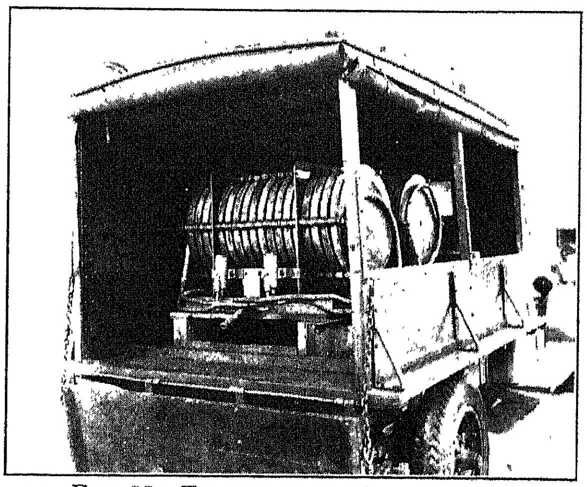

FIG. 38—TRANSPORTING TREATED OIL

oil in all underground portions of the cable, and special heaters have been installed to care for those portions of the oil system which may be exposed to temperatures below the flow point. The oil pipe runs from the tank towers to the terminals in both New York and Chicago are boxed in and may be heated when necessary from the heaters which are installed in all the tank houses.

Before any oil was used for filling the central core of the cable, joint casings, or oil tanks, it was necessary to submit it to a special treatment to remove all moisture and dissolved gasses.

In Chicago the towers provided convenient locations for the installation of this oil treating equipment, but in New York it was necessary to install a central oil conditioning plant and transport the treated oil from this point to the various reservoir manholes. Standard feeding reservoirs mounted on trucks were used for this purpose; see Fig. 38.

Cable Evacuation and Impregnation. As a preliminary, the engineers who were to perform the major operations

required during evacuation and impregnation were given special training. The training in Chicago was greatly facilitated by the use of a dummy set-up, representing a mile section of line, consisting of several short lengths of cable with high and low spots, and connected by glass tubing so that the men could see what was happening. In order that the men could become familiar with field operations, the apparatus which was actually to be used was connected to the ends of the set-up as shown in Fig. 39.

The cable was impregnated one section at a time, the first step being to evacuate and fill the reservoirs with oil, after which the cable was put under vacuum by means of vacuum pumps connected at each provisional and stop-joint on the section. This evacuation was maintained for approximately 12 hr. for drawing out any gas or surplus oil in the core of the cable.

As shown on the profiles, there were many high and low points along a section of line; and slugs of oil were formed at the low points, while gas would collect at the higher points. A suitable test was made at the beginning of evacuation to determine the height of these

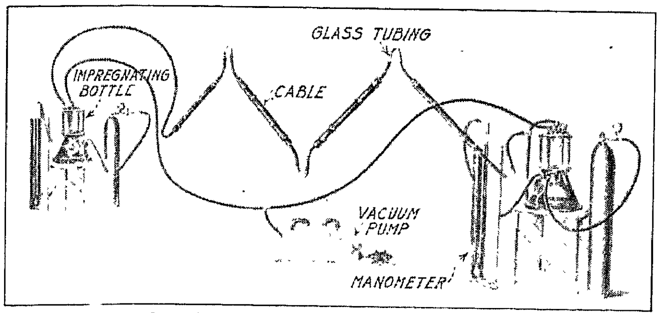

FIG. 39—DUMMY IMPREGNATION SET-UP

slugs opposing vacuum between adjacent provisional joints. The maximum and average heights for the slugs were, respectively, 10 and 3 ft. This "slug" test served also as a check on the continuity of the cable core and connections and permitted a prompt discovery of leaks or stoppages.

After the initial 12-hour evacuation period, tests were made to determine if slugs of oil still existed in the low points of the line which would interfere with obtaining a satisfactory vacuum at all points of the section. After these tests proved satisfactory, the line was evacuated for approximately 36 hr. If a good vacuum was then maintained and no leaks occurred, treated oil was admitted to the line.

At the beginning of the impregnation of a section, oil was admitted to only one phase, the second phase being connected when the first was about one-third filled, from 8 to 24 hr. later, depending upon the flow of the oil and the contour of the section. The third phase was connected when the second was about one-third filled. Upon the arrival of the oil at each provisional joint, it was first drained off into test bottles for testing and then the oil was allowed to flow into the impregnating bottle until the flow reached a satisfactory value. After the pressure of the oil had become greater than atmospheric, the apparatus was disconnected and the joint closed.

Because of the difference of line contour and location of feeding tanks, the process of evacuating and impregnating the cable differed somewhat in the two cities. In New York the treated oil was admitted directly to the line from the transportation tanks, which were connected to the cable at the stop-joint manhole located at the high end of the section, while in Chicago it came directly from the conditioning plant in the tower.

In Chicago and at the Dunwoodie tower in New York, on account of the possibility of leaks in the potheads or piping which would let in air at the time of impregnation, the oil was fed from the reservoir floors in the towers to the first manhole of each section; then the oil would feed not only forward into the cable but backward into the pothead and the vacuum maintained ahead of the oil would draw out any air which might come in through possible leaks.

In both New York and Chicago, the rate of oil flow was hastened by heating the conductor with low-voltage current when the low temperatures unduly increased the viscosity of the oil. On some sections in New York, accelerated flow was obtained by feeding in the oil at a provisional joint after the incoming oil had passed that joint. When the cables had been filled with oil and the provisional joints sealed, the valves connecting the reservoir tanks were opened.

From a knowledge of the cable temperature, oil viscosity, pressure heads, and cable profile, it was possible to predict approximately the speed of oil flow along the cable core, and thus to have engineers available for supervision at the provisional joint manholes when the oil arrived at these locations.

The time for evacuation and impregnation of a section varied from four to six days. The cable was then allowed to stand for two or three days before being given an impregnation test. The details of this test have already been described and characteristic results of the tests are shown in Fig. 12. If this test proved satisfactory, the provisional joints were opened, the flow of oil was stopped by inserting the screw in the hole in the connector, and the taping of the joint was completed, converting it into a permanent joint.

Joint Impregnation. After a section of the line had been impregnated and the temporary joints converted into permanent joints, the next operation to be performed was the impregnation of the joints. The General Electric and the Pirelli joints required two different methods of treatment.

The Pirelli joints were given an initial heat by means of special electric heating pads supplied from a battery on the truck where other electric power was not available. After the joints had been evacuated, oil was admitted from a special feeding tank.

The impregnation of the General Electric joints required no heat treatment and consisted only of a comparatively brief vacuum treatment and filling.

After the Pirelli joints had been impregnated, they were immediately reinforced with copper bands which were wiped on as a reinforcement for the lead sleeve against the internal oil pressure.

A good idea of the time required for the various processes described is given in the "Progress of Work" diagram shown in Fig. 40.

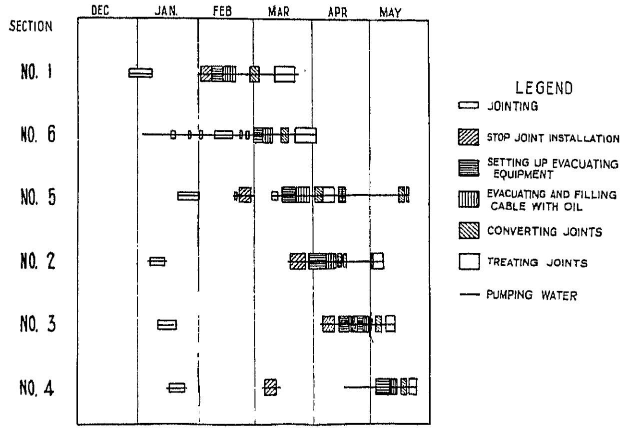

FIG. 40—"PROGRESS OF WORK" DIAGRAM—CHICAGO

Bonding. As originally planned, the two lead sheaths of the 132,000-volt cable were to be insulated from each other. It was actually found, however, that in many cases these leads were in contact after the cable had been pulled into the ground. For this reason and also because there was a possibility of dangerously high induced voltages if the outer lead were left floating, the two sheaths were wiped together on each side of each joint. In Chicago, the three cables also were solidly bonded in each manhole. With this bonding, the sheath current is about 50 per cent of the current in the copper and the sheath losses nearly equal the copper losses.

In New York the sheaths of the three cables were bonded at about 1000-ft. intervals in certain straight joint manholes, selected from an electrolysis survey of the line, but in all stop-joint manholes they were bonded on each side of the stop-joint and the two bonds connected.

Transposition. In Chicago, the 6-mi. underground line is in series with 30 mi. of overhead line; that is, the cable has only a small percentage of the total impedance of the tie line; therefore it was practicable to install the underground cables without transposition to balance the impedance of the phases. In contrast, the cable in New York formed the entire tie line and, therefore, to obtain equal impedances of the phases, they were transposed at eight points along the line.

Fireproofing. The final operation was to give the cables a fireproof covering in the manholes. In Chicago, this consisted of a layer of 1/8-in. asbestos tape applied with a butt lap, over which was the usual rope and cement fireproofing. The tape was applied because the lead sheaths were so thin it was considered best to protect them against any damage that they might suffer from cracking of the cement or breaking it off, should such a step be necessary for repairs.

The New York companies used their usual type of fireproofing, consisting of metal lath and cement on the greater portion of the line; and a new type consisting of an asbestos netting and special fireproof cement on the balance.

Testing Set. Each utility has purchased a special 400,000-volt, 0.25-ampere, direct current, Kenotron cable testing outfit, installed at Hell Gate and Northwest Stations in buildings constructed especially to contain them; see Fig. 41.

These sets are the largest ever made up for commercial use and a minimum space 30 ft. by 30 ft. by 30 ft. is needed for the set alone, exclusive of that required for cable terminals, switch gear, etc. For the purpose of assisting in the location of any failures that may develop during tests or operation, the Kenotron tubes have been arranged so that they may be connected to give higher currents at lower voltages, the maximum current rating being two amperes at 50,000 volts.

The test agreed upon, of 300,000 volts for 15 min., was applied to each phase separately without breakdown or indication of weakness in either the New York or Chicago cables.

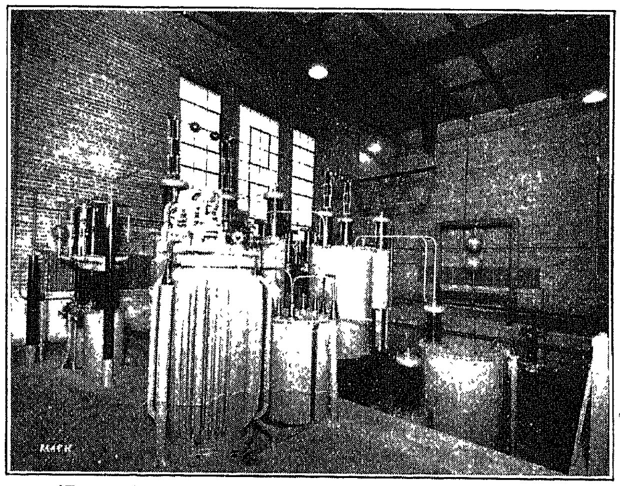

FIG. 41—KENOTRON TESTING SET—CHICAGO

OPERATION

There have been no electrical troubles from the time the cables were put into operation, June 2 for Chicago and August 9 for New York, to the time of writing, October 20; but there have been oil leaks which required repairs in stop-joint, gasket of pothead, joint wipes, pressure tanks, and lead jacket of cable section. In all cases, it has been possible to maintain the line in service until convenient to take it off for repairs.

The maximum load on the lines has been about 45,000 kv-a. The manufacturer's guarantee included a maxi-

mum allowable copper temperature of 65 deg. cent., a maximum power factor at that temperature of 1.25 per cent and a carrying capacity of 91,000 kv-a. The insulation of the cable as delivered, however, had a power factor of 0.5 per cent which permits an increase in the rating under identical field conditions to 98,000 kv-a.

The charging current of the underground line is 2400 kv-a. per mi., or about 25 times the value for a 300,000-cir. mil overhead line of the same voltage. The underground installation in Chicago is equivalent to a synchronous condenser of about 14,000-kv-a. capacity and the corresponding figure for New York is 28,000 kv-a.

Inspection and Signaling. Special equipment, processes, and plans are being worked out and special crews of men have been selected and trained to locate and repair any failures that may occur. Regular routine inspection is being made of the feeding reservoirs and of all manholes and the quantity of oil in the feeding reservoirs and water conditions noted and recorded and any unusual conditions reported at once.

The lines are provided with the usual automatic switches to open in case of failure and additional devices will be provided to indicate oil leaks as the life of the cable is brief, if it is not entirely filled with oil.

Repairs. As the cable has a hollow conductor filled with a very fluid oil, special provisions have been made for repairing the line so as to reduce, as far as possible, the entrance of air and moisture if the oil runs out. Experience indicates the feasibility of confining the damage occurring in this manner to the length of cable on which the trouble occurs, provided that the devices for indicating loss of oil are reasonably accurate and reliable. When necessary to remove and replace a length of cable, arrangements can be made by suitable connections so that there will be a continuous but slight flow of oil out of the cable, thus preventing the ingress of air or moisture. The plan of operation and the details of the devices and methods to be used for this purpose had been discussed at some length by the representatives of the several companies, and a leak in the cable sheath which developed about two weeks after the New York cable was placed in service gave an opportunity to try out these plans. The periodic inspections of the oil reservoir tanks showed that there was a loss of oil at a slow rate on one phase of a section and by inspecting manholes a location was found where oil was leaking out from between the inner and outer lead sheaths on a length of cable. The oil leak was very small, about five cu. cm. per hr., and the cable could have been left in service for weeks if necessary, but it was decided to replace the section promptly.

The static oil pressure on the defective section was about 30 lb. per sq. in. and the change was accomplished with the loss of only a few gallons of oil and without permitting air to enter the good cable on either side of the replacement.

The oil core of the phase to be repaired was connected at the end of the section remote from the feeding reservoirs to the oil core of an undamaged phase thus allowing a continuous flow of oil from both directions toward the repair during all subsequent operations.

The length of cable to be removed was then cut in both manholes so as to leave the joints connected to the two good ends.

Each joint was then taken down by unwiping the lead sleeve and removing the applied insulation and a hole was drilled transversely through the connector and reamed to a taper. During these operations the oil was allowed to flow, thereby preventing the entrance of air into the cable. A long tapered plug was then inserted in the reamed hole so as to block off the flow of oil from the good side of the cable. The defective length was then unsweated from the connector and the replacing length sweated in, and a provisional joint made up. The cable was then evacuated through the two joints, oil admitted, and the joints converted into permanent joints.

Experience has shown that a leaky wipe on a joint in a manhole can be repaired in about 2 hr. by draining the oil out of the joint so as to remove the internal pressure. A stop-joint was replaced in about 15 hr. and a section of cable in 2½ days. It is thought that a failure in a joint which does not involve replacement of cable can be made in approximately 36 to 48 hr. If the trouble or the replacement of the length of cable involves the entrance of a large amount of air into the cable, then it may be necessary to repeat the original process of evacuation and impregnation, requiring considerably greater time.

The time for all of these operations, however, will vary, depending on the location of the trouble and the profile of the section.

Conclusion. From the foregoing details it may be seen that many vital features employed in the manufacture, installation, and impregnation of this type of cable will also impart a new direction to the attainment of better and more reliable cables of the ordinary type. The indications are that this cable marks a new epoch in cable engineering.

Discussion

H. L. Wallau: This development marks a substantial advance in the art. From the design data submitted by Emanueli in the maximum working stress appears of the order of 160 kv-in. (63 kv-cm.)—over three times the safe limit set by Shanklin and Matson in 1919. This value assumes non-graded insulation of uniform specific inductive capacity.

Two years ago the speaker made a study of the probable dimensions of single-conductor paper-insulated cables of the ordinary type for use at a maximum potential of 80 kv. to sheath. Maximum working gradients of from 50 to 150 kv-in. were used and the R/r value of the cables set at 2.72. A lead sheath of 9/64-in. thickness was assumed. Typical results were as follows:

Maximum Working Stress, Kv-in.	r Inches	R Inches	Overall Dia. Inches	Safety Factor
50	1.600	4.33	8.94	5.30
100	0.800	2.17	4.62	2.65
150	0.533	1.45	3.19	1.77
The Pirelli cable yields				
160	0.610	1.315	3 approx.	3.5 to 4 From tests

The safety factor of a cable may be defined as the ratio of the indefinitely sustained breakdown voltage to the operating voltage, or

$$\text{S. F.} = \frac{\text{Breakdown voltage}}{\text{Operating voltage}} = \frac{\text{Breakdown gradient}}{\text{Operating gradient}}$$

Except in the case of Pirelli cable, the numerical values given were obtained by using a sustained breakdown gradient of 265 kv-in. for impregnated paper insulation, based on test data by Peek.

This study led to the conclusion that for such cables working stresses of 150 kv-in. were required since they alone yield cables of reasonable diameter and weight. The danger lay in the low safety factor obtaining.

The test results on the present type of 132-kv. cable reported by W. S. Clark indicate a sustained breakdown voltage of some 260 kv. to 300 kv. or a safety factor of between 3.5 and 4.

This increase in safety factor has apparently been accomplished by two means:

1. The insulation seems to have been graded, not by using different impregnating compounds and one quality of paper but by a reversal of this method, which lends itself particularly well to commercial production, namely, the use of a single compound and of several qualities of paper. Is this supposition correct? What is the calculated maximum working stress in kv-in?

2. Ionization has been practically suppressed by the complete exhaustion of all gases from the cable after installation, the filling of all voids within the cable with suitable oil and by maintaining that condition over the working cycle of the cable, coupled with an internal pressure head, never less than atmospheric, which prevents the entrance of air or moisture.

Incidentally, these cables are guaranteed to operate at a temperature of 65 deg. cent. or 5 deg. higher than the "maximum safe temperature" set up in the A. I. E. E. Standards No. 30. The speaker was instrumental in having the old rule of $t = 85 \text{ deg.} - E$ modified and suggests that the new standard be further revised to make it accord with present practise.

The reasoning and methods employed leading to the determination of the locations of feed and pressure tanks are exceedingly ingenious and the field impregnation test equally so.

The two types of joint used differ in details. It is interesting to note that machine wrapping is being used in the Pirelli joint and a copper instead of a lead sleeve used in the General Electric joint. It is believed that the Cleveland 66-kv. joint was the first in which either of these two things was done, brass, instead of copper sleeves, being used in Cleveland.

Mr. Torchio has dealt somewhat with the economic aspect of this development, but has not touched on cost. It is rumored that these initial installations are more costly per kv-a. than 66-kv. circuits including 2-to-1 stepup transformers. It is possible that future installations will decrease in cost somewhat, and possible also that for higher-voltage circuits the cost per kv-a. may show an appreciable reduction over that for 132-kv. circuits. Comparisons of cost per kv-a-mi. for voltages of 132-kv. and 220-kv. would be of interest.

There are two points relating to details that are not quite clear. How is the core of the heated cable exhausted? Mr. Clark states that the ends of the cable section are sealed after heating and insulated leads brought out through the seals, after which the vacuum is applied.

In the paper descriptive of the installation methods occurs the statement: "The oil core of the phase to be repaired was connected at the end of the section remote from the feeding reservoirs to the oil core of an undamaged phase, etc." Does not the making of such a field connection require the opening of a joint in one of the undamaged lines?

H. L. Wallau (communicated after adjournment): The tabulation given in my previous discussion may be extended to cable for operation at 220 kv. (nominal) using the same R/r ratio. In this case, the voltage between conductor and sheath will be 133.5 kv. allowing the conventional 105 per cent. of nominal pressure as maximum circuit voltage.

Maximum Working Stress, Kv-in.	r Inches	R Inches	Insulation Thickness Inches	Over-all Diameter, 9/64-in. sheath
150	.891	2.42	1.53	5.12
160	.834	2.26	1.43	4.80
200	.678	1.84	1.16	3.96
250	.534	1.45	.92	3.18
300	.445	1.21	.77	2.70

It is fair to assume that manufacturers today cannot produce oil-filled cable which may be operated at a maximum gradient exceeding 160 kv-in. with the factor of safety now believed necessary for such important service, involving powers of the order of 150,000 kv-a. per circuit at 220 kv. Factors of safety are measures of ignorance. Hence, operating experience with the 132-kv. cables may disclose that a factor of safety of from 2 to 2.5 is quite liberal, which would permit of gradients of the order of 250 to 300 kv. per in. Such gradients would bring 220-kv. cables in the 3-in. diameter class.

Mr. Roper has stated that the Chicago installation cost complete including conduit, cable, towers, tanks, etc., is $1,250,000 for a 6-mi. line of 98,000 kv-a. capacity. This yields a cost of $2.13 per kv-a-mi. If experience proves that this cable might safely be operated at 220 kv. with the same ampere loading or 163,000 kv-a. the cost per kv-a-mi. would be reduced to $1.28. The cost of the 66-kv. cable installation in Cleveland, complete in every detail, based on a conservative rating of 35,000 kv-a. per circuit, is $1.62 per kv-a-mi. Two circuits each 8¼ mi. are installed.

F. A. Brownell: The cable installations in New York and Chicago have shown a great advancement in the art of underground transmission. Apparently we will have to change our concepts regarding high-tension cable, both in regard to cost and installation, for it is quite obvious, after witnessing the moving pictures of the installations, that the cost must have been considerable.

Mr. Emanueli, in a footnote, mentions "all the delicate operations of installation and impregnation." That "delicate operations" is a new term to most of us. Ordinarily we do not think of delicate operations in connection with cable installation but if we did we might lessen some of our troubles.

The following statement seems rather startling, "All these difficulties and uncertainties would not have allowed the design of a 132-kv. cable of the usual type with any probability of success."

It would be interesting to know whether or not the American cable engineers are in agreement with this statement as some of the preliminary tests made on the usual type of cable have been encouraging.

J. B. Whitehead: Mr. Clark has mentioned the electrical characteristics of these cables. He stated that he had found a descending power-factor-voltage curve indicating a negative ionization coefficient, and that this fact caused him and his associates some disquiet, because they saw no obvious explanation. Having visited my laboratory in Baltimore and learned that we too had found such curves, he was somewhat relieved,

but not yet satisfied. He then stated that he subsequently found that the explanation of his descending power-factor-voltage curves was found in an error introduced into his air condenser, owing to the high moisture content of the air; and that having eliminated this source of error he found that his power-factor curves came back to a flat shape, thus indicating that he attributed the apparent descending power-factor curve to an error in his method of measurement. He did not tell you, however, what he thought of our descending power-factor curves, but the obvious inference is that he attributes them to a similar source of error. I want to correct that impression.

It may be true that in the presence of moist air, that is to say, a relative humidity of about 80 per cent, an open-air condenser may take on a power factor which is other than zero. If it does, and incidentally I doubt it, such an error will cause a decrease in the apparent power factor of a cable measured in the Schering bridge in the usual connection. However, the apparent decrease of power factor owing to such an error is not nearly as great as the decrease that may be observed under certain conditions in the power-factor-voltage curve of perfectly impregnated insulation.

We have found dozens of such decreasing power-factor-voltage curves. They are inherent in all thoroughly impregnated insulation when the temperature is above 40 or 50 deg. Below this temperature such insulation shows a perfectly flat power-factor curve, but above the temperature mentioned there is a maximum power factor at relatively low voltage gradient, decreasing thereafter towards higher values of gradient.

I believe that there is a sound theoretical explanation of this decrease in power factor. The power factor of impregnated paper insulation is intimately connected with the conductivity characteristics of the impregnating compound. The conductivity of these compounds is due to the motion of ions which probably consist of aggregates of molecules surrounding a central charge of molecular or atomic dimensions. It is well known that this type of conductivity has an initial limiting value at any temperature. As the voltage rises the ions are drawn out of the liquid more and more rapidly until finally the conductivity is greatly lessened, being that corresponding to the rate at which new ions are generated or liberated in the liquid. This conductivity has in general a much lower value than the initial value. Thus as the voltage goes up the charging component of the current goes up, but the conductivity component of the charging current remains fixed and the power factor therefore comes down.

R. W. Atkinson: I wish to say a word about a point concerning which Dr. Whitehead has spoken. We have found, as has he, that some types of cable dielectric do show very definitely a decrease in power factor with increasing voltage. Our standard of reference has been an air condenser with a dielectric of compressed gas (very dry, compressed carbon dioxide). Many types of check measurements, carefully repeated at intervals over a term of several years, have given us great assurance in these measurements showing decrease of power factor in certain dielectrics, with increase in voltage.

Our experience as to the type of dielectric most likely to produce this condition is also parallel to Dr. Whitehead's, namely, well impregnated dielectric, tested at high temperatures, that is within the range of 60 to 100 deg. cent. In our case, characteristics of this kind associated with saturated paper have seemed to occur particularly where the impregnating medium is a relatively fluid oil.

No one needs to be told how great is the accomplishment that has been described in this paper. Transmission of power by cables at 132 kv. until so recently the limit of extensive overhead transmission, is recognized at once as a great advance in all electrical industry and can be appreciated by the executive who is concerned with financial problems, by the engineer who is a specialist in some other line, the general engineer as well as by the transmission engineer.

However, many may not appreciate the magnitude of the work done in arriving at this finished result. The authors have been modest in describing the development of this work and have presented to us a finished product, a procedure that always makes an accomplishment seem easy.

Aside from those taking part in this particular development or directly associated with it, only those who have had to cope with related problems can adequately appreciate the magnitude of the physical task performed. I want, therefore, to congratulate these men and the manufacturing and operating companies they represent, for their great vision as well as for their painstaking efforts in overcoming the obstacles in the way of accomplishment.

W. A. Del Mar: There is one aspect of the installation which especially interests me as a cable manufacture, and that is to see these two manufacturers, the General Electric and the Pirelli Companies, undertaking the major part of the engineering work. I do not mean to belittle what has been done by the operating companies, but we have been seeing a growing tendency, in recent years, toward the operating companies taking over more and more of the design details of cable installations. Here we have a return to the practise of leaving the major responsibility to the cable manufacturers, which I think is a healthy sign.

The manufacturers appear to have taken this responsibility with a full appreciation of the difficult and intricate engineering features involved and they are to be congratulated on having produced a model installation.

We are, however, only at the threshold of 132,000-volt cable developments and it may be found that many of the complications are unnecessary. There are at present, both at Chicago and Newark, experimental installations of 132,000-volt cable, some of which are of the ordinary design and they have been successfully carrying voltage for several months.

The question of the breathing of the cable, that is to say, the expansion and contraction of the oil in and out of the cable, is, of course, a very important feature of the installation. It would be interesting to know whether this expansion, which forces oil from the cable into the reservoir, is of the magnitude to be expected from the expansion of the oil in the hollow core only, or whether the expansion is greater than that and involves part or all of the oil which is with the paper.

Mr. Emanueli's paper bases the theory of this installation upon the idea of maintaining constant the impregnation of the cable by providing for the effects of changing temperature. We should not forget that it also involves the maintenance of a certain variable hydrostatic pressure within the cable which, according to this paper, varies from 1 to, I think, 3 or 4 atmospheres, so that probably the cable, during most of its operation, is at considerably above atmospheric pressure. The dielectric strength of the insulation, and its capability of resisting ionization are greatly increased by the hydrostatic pressure. Possibly in going to higher voltages, which I think we can see clearly before us now, that aspect of the design will have to be given more consideration.

F. M. Farmer: The essential feature of this type of construction, of course, is the application in as nearly an ideal way as possible of the theory which has been recognized for a long time as being essential in insulation, namely, the complete removal of gas and voids from the insulation (which means in the case of cable insulation not only the complete removal of gas and voids from the paper but also from the oil) and the maintaining of this condition under all conditions of operation. In other words the complete insulation structure must be kept in its proper condition at all times.

It is evident, of course, that this construction must have been expensive. There might be some question in the minds of some operating men as to the economic justification for these installations—some question whether the present state of the art

justifies the expenditure involved. I think we ought to look just a little ahead.

If this type of construction proves successful, and the chances seem to be excellent that it will, it demonstrates in the first place that there probably is no reasonable limit to the voltage at which underground transmission can be made. Two hundred and twenty thousand volts is obviously in sight under those conditions, and the economic phase of the situation then takes on an entirely different aspect. Costs that might not be justifiable at 133 kv. might be entirely at 220 kv.

In the second place, if this principle is shown to be the solution of the high-voltage cable problem, won't means be found for applying it at moderate voltages at considerably less expense? So I say that this large-scale experiment, as it might be called, is going to be of real value in demonstrating the correctness of this fundamental theory. Despite the fact that this theory has been with us a good many years, there have been conflicting evidences as to its importance. This installation is going to demonstrate once and for all the soundness of that fundamental theory. If the theory is proved then the expenditure on the part of these two companies will be amply justified, and as some of the speakers have said, the industry will owe these companies a great debt, for their foresightedness and their courage in going ahead with this very expensive undertaking.

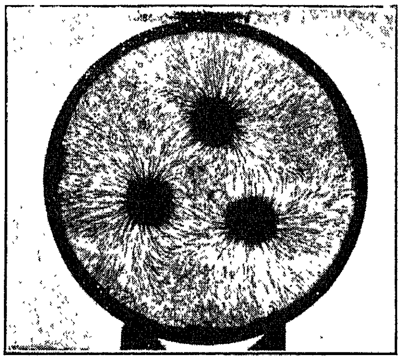

Fig. 1

E. B. Meyer: I might say that in the Public Service System of New Jersey there is an experimental installation of a 132,000-volt cable. The cable was furnished by three manufacturers, and each manufacturer was allowed, in designing the cable, to bring forth his own ideas, each type of cable being one phase of the circuit approximately 1000 ft. in length, a total of 3000 ft. of cable. The cable is constructed somewhat on the order of cables operating at lower voltages.

One cable is a hollow-core type filled with compound, another of a concentric type, and still a third one has a rope core. The cables are not oil-filled. The joints are both machine-made and hand-wrapped, using paper and varnished cambric. The cable has been under potential since February of this year, and on June 1 it was placed in service carrying load.

C. F. Harding: Following the suggestion of Dr. Whitehead, not only does that field of intensity change very greatly within the dielectric with the change of voltage, but it departs materially from any calculated field which would be expected in a single-phase cable, and particularly in a multiple-conductor cable.

The accompanying illustration is a photograph of this field in a cable model. In the methods which have been used in this particular demonstration,[1] not only is the field, and therefore the intensity, about the surface of the conductors at different points very greatly changed with increased voltage but we also have a sufficient mechanical moment in the dielectric to produce an actual rotating field.

We wondered at one time what that blur on the photograph was, and what the apparent difficulty in visualizing the field might be, but after inspecting carefully and taking several photographs the cause was found to be the actual rotating of the particles in the dielectric itself, in the multiple-conductor cable.

Such a method of visualizing and analyzing the dielectric field by photographic means, possibly with the motion picture camera, applied to the actual motion within the dielectric at higher voltages, may throw some light upon the test values, maintenance costs, and possibly the cause of breakdown of such high-voltage cables.

G. B. Shanklin: The principle of a liquid-oil filler to prevent void formation in high-tension fibrous insulation is so firmly established and has such preponderant evidence back of it that little need be said here.

To my mind, the most convincing evidence is found in the evolution of high-voltage capacitors for power-factor correction. For reasons of economy it is necessary to operate the dielectric in these capacitors at a working stress several times higher than that in cables of the ordinary type. Every conceivable form of insulation was tried, no limits being set by mechanical requirements, such as flexibility, etc. Paper, carefully evacuated and impregnated with a liquid oil, submerged in this oil and sealed off from the atmosphere, proved to be in a class by itself. No other form of dielectric could even approach it from the standpoint of economy and safety.

To work out and apply these principles in a practical way to a long line of 132,000-volt cable was a vastly more difficult job. The papers presented today show how it was done, and to the Pirelli Company belongs the major credit for their initiative and foresight.

It should be remembered that these lines are pioneer installations. Invaluable experience has been gained which will, in future installations, result in very material savings in economy and simplicity.

A great deal of attention has recently been centered upon the possible use of ordinary solid cable, that is, cable impregnated with very viscous compounds, for 132,000-volt operation. I should like to point out that our company was one of the first to attack the problem from this angle. We have had trial lengths of this type of cable operating on the 110,000-volt lines of the New York Power and Light Corporation for more than three years and propose to continue our experiments.

Our present conclusions are simply these. The solid-type cable can be made to operate more safely by oil-reservoir feed from the joints. No doubt the present limit of 66,000 volts can be raised by taking every possible precaution. Whether we shall ever reach successful 132,000-volt operation is very doubtful. If so, one thing is certain, we shall be too near the ragged edge for comfort and cannot hope to approach the operating record of the liquid-oil-filled-cable, with its greater factor of safety, both from the standpoint of voltage stressing and current loading. From an economic standpoint it is my opinion that the liquid-oil-filled high-tension cable will eventually be on equal terms with solid cable of the same voltage rating, due to reduction in insulation thickness and the greater allowable temperature range, or current loading.

Finally, we should look ahead to the future, as Mr. Torchio has so ably pointed out, for the day will come when 220,000-volt cable will be needed.

K. W. Miller: In the study of oil movements in single-conductor cable in general as well as in the determination of the lengths of sections of line between stop joints and in the design of the reservoirs, pressure tanks, and cable, it is important to be able to predetermine oil flow and pressure drops along the section during load changes. Since the rate of oil flow depends on the rate of temperature change and since also the friction drop is

1. "Improved Method of Visualizing and Photographing the Dielectric Field," by R. H. George, K. A. Oplinger, and C. F. Harding, *Bulletin* of Eng. Exp. Station, Purdue University.

directly dependent on the viscosity of the oil, which in turn is dependent on the temperature, it follows that from a complete solution of the cable temperature transient under any assumed conditions it would be possible to predict oil flows and pressures with considerable accuracy. Such a solution is possible for the cases of cable cooling after load removal by the use of Bessel functions.

Mr. Emanueli has derived approximate values for these quantitites which he calls a and b using several simplifying assumptions, and from them determined the general layout of the oil system. The static pressures and the reservoirs are so large that considerable inaccuracies in the determination of oil flows and pressure drops are not very important. However, long sections, oil towers, and high oil pressures requiring reinforced lead sheaths, and causing frequent oil leaks, are all disadvantages that will probably be eliminated on any future lines. With smaller static pressures, the pressure drops with changing load will be more important, and also the pressure drop due to the radial oil flow through the insulation will become relatively more important.

The question of the relative merits of oil core and fluted lead-sheath oil ducts, also requires a more thorough analysis of the temperature transient. Knowledge of this thermal transient is quite important in consideration of voids and compound migration in lower-voltage cables not oil-filled. Therefore, it appears worth while to analyze the thermal transient more exactly.

Let us consider a cylindrical element of insulation of unit length at radius x and thickness $d\,x$. In addition let

t = time in seconds
r = inside radius of insulation
R = outside radius of insulation
Q_1 = thermal capacity of copper and free oil per unit length
Q_2 = thermal capacity of sheath per unit length
q = specific thermal capacity of insulation per unit volume
p = specific thermal resistance of insulation per unit volume
E = thermal resistance, sheath to duct per unit length (assumed constant)
T = temperature deg. cent. at point considered
T_0 = duct temperature—assumed constant over initial period of transient
W = watts heat flow across circular element at x
W_e = watts heat flow sheath to duct
e = volumetric thermal coefficient of expansion of oil and paper insulation
a_1 = rate of oil flow contributed by core per unit length
a_2 = rate of oil flow contributed by insulation
a_3 = rate of oil flow contributed by thermal shrinkage of sheath
a = total resultant rate of oil flow, per unit length.

The rate of temperature change in an element of volume ΔV is directly proportional to the heat generated in the element, to the differential of heat entering and leaving the element, and inversely proportional to the heat storage capacity of the element. Setting up this relation and simplifying we get

$$2\pi q \frac{\partial T}{\partial t} = -\frac{1}{x}\frac{\partial W}{\partial x} + \frac{k\,(D.\,L.)}{x^2} \tag{1}$$

where the last term represents the effect of dielectric loss on the assumption that the dielectric power factor is constant, independent of voltage gradient. Variation of dielectric loss with temperature can be approximated by a method not discussed here.

The differential temperature drop across an element is directly proportional to the heat flowing across the element and to the heat resistivity of the element. Setting up this relation and simplifying we get:

$$\frac{2\pi x}{P}\cdot\frac{\partial T}{\partial x} = -W \tag{2}$$

Differentiating (2) with respect to x and substituting into (1)

$$p\,q\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{1}{x}\frac{\partial T}{\partial x} + \frac{k\,(D.\,L.)}{x^2}$$

This equation cannot be exactly solved in general due dielectric-loss term. However, for the most important c dropping both voltage and current this term automa disappears except for the initial condition where it can eas handled.

A solution of (3) for opening the switch and "killing the which is sufficiently general to satisfy all limiting conditi

$$T = \sum_{n=1}^{n=\infty} e^{-\frac{u_n^2 t}{pq}} \left[A_n J_0(u_n x) + B_n Y_0(u_n x) \right] + T_0$$

where A_n and B_n are not independent.

The limiting conditions in time are

$$t = 0, \quad T = f_1(x) \quad (f_1 \text{ known})$$
$$t = \infty \quad T = T_0$$

and in space are:

$$x = r, \quad \frac{\partial T}{\partial t} = -\frac{W}{Q_1}$$

$$x = R, \quad \frac{\partial T}{\partial t} = \frac{W - W_E}{Q_2}$$

$$W_E = \frac{T - T_0}{E}$$

Combining (8) with (7) and then (2) with (6) and (7) we get

$$x = r, \quad \frac{\partial T}{\partial t} = \frac{2\pi r}{p\,Q_1}\cdot\frac{\partial T}{\partial x}$$

$$x = R, \quad \frac{\partial T}{\partial t} = \frac{-2\pi R}{p\,Q_2}\cdot\frac{\partial T}{\partial x} - \frac{T - T_0}{E\,Q_2}$$

Differentiating equation (4) and substituting it into equa (**6a**) and (**7a**) and simplifying we obtain the following equa for determining the roots U_n and the relation between cons A_n and B_n

$$\frac{-B_n}{A_n} = \left[\frac{M_1 - \phi\left(\frac{r}{R}Z\right)}{M_1 - \psi\left(\frac{r}{R}Z\right)}\right]\theta\left(\frac{r}{R}Z\right)$$

$$= \left[\frac{M_2 + \phi(Z) - \frac{N}{Z^2}}{M_2 + \psi(Z) - \frac{N}{Z^2}}\right]\theta(Z)$$

where $M_1 = \dfrac{Q_1}{2\pi q r^2}$, $M_2 = \dfrac{Q_2}{2\pi q R^2}$, $N = \dfrac{p}{2\pi E}$

and

$$\phi(x) = \frac{J_1(x)}{x\,J_0(x)},\quad \psi(x) = \frac{Y_1(x)}{x\,Y_0(x)},\quad \theta(x) = \frac{J_0(x)}{Y_0(x)},\quad Z =$$

Equation (9) may readily be solved graphically for the three roots $Z_n = R\,U_n$. Since the time exponents in equa (4) vary as $(u_n)^2$, the series rapidly converges for all except short times. But for zero time, knowing copper loss, diele loss, sheath loss, and $f_1(x)$, the temperature derivatives ca obtained directly from equations (3), (6), and (7). There the first three terms will give ample accuracy.

Values of the constants A_n can be determined by equa equation (4) equal to $f_1(x)$ at time $t = 0$ and giving n f values to x and solving for the coefficients A_n. The natur the Bessel functions is such that $f_1(x)$ can be closely appr

mated with three terms. Equation (4) is now completely determined.

If we take the time derivative of equation (4), we may multiply it by the elementary volume and by the unit volumetric coefficient of shrinkage for the insulation and integrate for the total oil demand of the insulation.

$$a_2 = \int_r^R - 2\,\pi\,\epsilon \left(\frac{\partial T}{\partial t} \right) x\,dx$$

$$= \sum_{n=1}^{n=\infty} \frac{2\,\pi\,\epsilon}{p\,q}\, e^{-\frac{u_n^2\,t}{pq}} \Big[A_n\,(u_n\,x)\,J_1\,(u_n\,x) + B_n\,(u_n\,x)\,Y_1\,(u_n\,x) \Big]_r^R \qquad (10)$$

If we let $x = r$ and $x = R$ in equation (4) we get the thermal transient of the copper and sheath respectively. The time derivative of the equation for $x = r$ can be multiplied by the thermal volumetric expansion coefficient of the copper and oil in the core to obtain that portion of the oil flow a_1 contributed by the oil in the core. Likewise the time derivative of equation (4) for the sheath when $x = R$ can be multiplied by the linear coefficient of thermal expansion of lead, properly applied, to obtain the volumetric shrinkage of the sheath, a_3. Then the total oil flow is $a = + a_1 + a_2 - a_3$.

It is interesting to note in the numerical application of these equations that with low dielectric loss and large sheath loss, or also for dropping load current only, then during the initial period the sheath shrinkage may be nearly equal to the volumetric shrinkage of the oil. For these conditions in extreme cases the oil flow a at time $t = 0$ may start at zero or even a negative value (reverse flow).

A remaining consideration is the natural elasticity of the cable. If we assume perfect impregnation it may be shown that with any reasonable assumption for the volumetric coefficients of compressibility of the oil and solids and of Young's modulus for the lead sheath and copper binding ribbon, that the elastic effect cannot possibly exceed the equivalent of 1 deg. cent. for the pressure changes involved. As 1 deg. cent. is only a few per cent of the maximum total temperature change of the cable for any condition, the elastic effect may be neglected without serious error.

Knowing the copper temperature transient (and with it the oil viscosity), the resistance coefficient which Mr. Emanueli calls b is known as a function of time. Therefore, the product $a\,b$ or pressure drop can be completely determined with the same accuracy as we can measure the various constants of the cable.

The oil system was designed to maintain the oil pressure in the central core above atmospheric pressure. However, it must be remembered that capillary forces are very considerable and the paper fibres having once been "wet" by the oil will draw oil in from the core even though the pressure in the core drops below atmospheric. Radial friction pressure drops are not large so that a considerable margin of safety exists for the prevention of voids. Oil flow as determined theoretically from equation (11) and experimentally in the field, checks within reasonable limits, indicating that no voids form in the insulation during the worst case, that is, killing the line after it has been carrying full load long enough to reach its maximum temperature.

H. R. Searing: One discussor asked the question about the paragraph "the oil core of the phase to be repaired was connected at the end of the section remote from the feeding reservoirs," and so forth.

There wasn't any joint opened. The connections were made at the stop joint. When we speak of the end of the section, we mean the far end, down at the stop so that the oil flows down hill on a good phase and back up the hill to the point where the repair is made.

I wanted to bring out a point that has been overlooked in the paper, that is, that the New York line, for instance, has a capacity effect amounting to about 29,000-kv-a., and I wanted to tell what that does to a central station system.

Naturally the major effect would be noticed at times of lightest load. It isn't predominant on the peak. These figures are for 4:00 a. m. in the winter when there isn't the ice-manufacturing load that we have in the summer. With a system load of 75,000 kw. before cutting the line in, the system power factor is 70 per cent, and after cutting in the line it goes to 80 per cent. The operating man will appreciate what that means on station economies. That is only one line.

What is going to be the result if you have ten lines such as that?

The second thing to point out is that with a nominal bus voltage of 13,800, if on cutting the line in you don't at the same time run the field rheostats down, the voltage at this time of morning goes to 14,600, and in cutting the line out from a nominal bus of 13,800 the voltage drops to 12,900. Voltage regulation of that character isn't a pleasant thing to deal with.

W. N. Eddy (communicated after adjournment): Throughout Mr. Emanueli's explanation of the formation of the gas bubbles and films in high-tension insulation, no mention is found of the influence of pressure on the solubility of gases in the impregnating oil. It seems as though this should form an essential part of such a discussion because as long as the air content of the insulation is in solution it is harmless. For instance his second reason for the presence of gas films—that the insulating compound carries in solution a great volume of gas, part of which is set free while the compound is passing through the paper during impregnation—is extremely difficult to accept. Instead, it seems more reasonable and in better agreement with experimental results to consider that when the impregnating compound first fills the paper, its gas content is all in solution, that no gas separates out until the local pressure is reduced by the formation of contraction voids. It is also indicated by results of experimental investigation that a proper impregnating procedure will keep the air content of the paper and compound sufficiently low so that it is not primarily responsible for the formation of bubbles or voids in the insulation.

The development of the oil-filled cable is further evidence that the quality of impregnated paper insulation is not yet limited by the type of materials in use. In attempting to determine how far distant such limits are, it is of interest to consider the dielectric strength of miniature units of the insulation in sheet form submerged in excess compound, as they provide maximum freedom of compound movement and therefore approach what is probably the ultimate quality obtainable with the materials in question. It is encouraging to note that three layers of low-air-resistance paper can be saturated in this form so that they will withstand without failure or any indication of deterioration, a stress of 750 volts per mil for over 18 months, even using compounds no thinner than a heavy cylinder oil.

Both Mr. Clark and Mr. Emanueli mention that while the oil filling does not change the short-time breakdown, it greatly improves the life of the insulation. The following test results (Table I) confirm this in indicating that sheet samples of insulation of the form above referred to, show considerable improvement in short-time breakdown over typical cable insulation but a still greater improvement in life. The figures given for cable insulation are believed representative of the best cables of the usual type now being manufactured.

TABLE I

3-conductor cable	short time breakdown....407 volts per mil	
	life at 75 per cent (305 volts per mil)......	0.7 hr.
1-conductor cable	short time breakdown....480 volts per mil	
	life at 75 per cent (360 volts per mil)......	5. hr.
sheet insulation	short time breakdown...1000 volts per mil	
	life at 75 per cent (750 volts per mil)......	1½ years

It is also interesting to note that when this sheet insulation is purposely saturated so as to include bubbles of air, its dielectric strength is reduced 50 per cent, to nearly that of single-conductor cable insulation, while the strength of the separate paper sheets is unaffected, remaining slightly less than the cable insulation.

TABLE II

Air Pressure above compound during Saturation	Short-Time Breakdown in Volts/Mil: Complete Sample of 3 Layers	Separate Layers
228. Cm.	590	382
0.02	1016	381

In general the quality of the sheet form of insulation mentioned above is believed to indicate that considerable improvement in impregnated paper insulation can yet be expected before the quality of such insulation will be limited by the type of material in present use.

Philip Torchio: Before answering the questions raised in the discussion, it is here recorded that the lines have continued in service to date (December 30) without any electrical failure in cables or joints.

Mr. Wallau has remarked that in dealing with the economic aspects of this development, figures of costs were omitted. The total cost for the New York 12-mi. installation when completed for 98,000 kv-a. will be \$4,100,000, or \$3.50 per kv-a-mi. The corresponding cost of a 66,000-volt line for 35,000 kv-a. would be \$2,200,000, or \$5.25 per kv-a-mi.

The total of \$4,100,000 includes \$950,000 in spare ducts and two terminal buildings, and testing equipment also available for future installations and other uses. The receiving end has double transformation and switches for 45,000 and 13,200 volts. Again, the cable obtained from Milan and the accessories, of entirely new and experimental design, built by Pirelli, had to bear oversea transportation and 35 per cent to 40 per cent import duty. In any future installations all material would be manufactured here, and, in addition, the heavy costs of experiment, research, and development in the factory, and of such extensive technical and research investigations in the field, will not be duplicated.

Any comparison of cost must, of course, take into account the wide differences in local conditions—especially those affecting subway costs, such as surface and subsurface conditions (which conditions undoubtedly greatly influence the comparison between Mr. Wallau's figures and these)—and savings in substation costs, synchronous condensers, transmission and transformation losses, etc., which also vary locally.

The increment cost for an additional feeder would be \$1.98 per kv-a-mi. for 132 kv. and \$3.00 per kv-a-mi. for 66 kv. All these figures indicate an outstanding economic saving for the 132-kv. cable line.

Even these relative comparisons are only approximately true, as the oil-filled cable can safely carry higher overloads and also is more serviceable in operation because a defective sheath will give a warning long before failure, while in solid-insulation cable it manifests itself by sudden electrical failure. These features may prove to be of definite economic value in enabling one to install considerably less reserve cable capacity than it is now safe to provide in installations using solid-insulation cable.

In New York, a most important consideration was that we should be in a position to receive into the city, when available, considerable amounts of bulk power delivered at high voltage from future water-power developments. The practical solution of this problem was felt to justify the advance investment in a line having a capacity three times larger than required in the very immediate future.

Our experience so far seems to point to the achievement of a new standard in cable operation, indicating the probability that such cable will have a reliability superior to any of the cables for lower voltages with which we have been familiar.

It is gratifying to report such satisfactory and epoch-making results, and to express due appreciation of the vital contribution made by the manufacturers and their engineers.

A. H. Kehoe: Mr. Torchio will supply the cost data for the New York installation in his closing written discussion. However, I should like to report that while the investments exceeded the minimum estimates, due to charges for supervision and some special unforeseen equipment, these did not cause our costs to be increased excessively. I believe that with future lines the costs will be scaled down so that even our early estimates will be materially reduced.

D. W. Roper: To give an idea of the complexity of the work involved in evacuating and impregnating the line after all the joints are first made up in a preliminary way and after the first section is installed so you then have all processes in progress in the various sections, the maximum number occurs during the evacuating and impregnating process. That takes something like four or five days and is a continuous process 24 hr. per day. The maximum number of men employed on the line in Chicago occurred when this evacuating and impregnating process was in progress on one section, and other portions of the work were in progress on several other sections, at which time the number of men was 125. This included about forty engaged on pumping operations and the representatives of manufacturers.

The total cost of the Chicago line including the conduit, the cable, the terminal towers, the intermediate towers for the oil reservoirs, the Kenotron testing outfit, and a reasonable proportion of the transformers and the terminals at the Northwest station, was \$1,250,000.

There have been no electrical failures whatever in either the cable or the joints in New York or Chicago. The troubles have all been confined to oil leaks.

W. S. Clark: The reason there was such a large supervision on the part of the manufacturers' engineers in the installation of this cable was that the manufacturers' engineers were more familiar with this new type of cable than were the utilities' engineers. If the installation were repeated in New York or Chicago, the amount of supervision by the manufacturers would be negligible.

Illinois Central Suburban Service*
First Year of Electric Operation in Chicago

BY W. M. VANDERSLUIS[1]

Associate, A. I. E. E.

Synopsis.—This paper gives operating records of the first year of electrical operation of the suburban service of the Illinois Central Railroad. It shows monthly curves of load, kw-hr. per car-mile, maximum demand, load factor, and temperature. It also shows monthly curves for the last four years of passengers, car-miles, seat-miles, and operating income. The improvements in service are enumerated and the general results at this date are discussed.

* * * * *

Steam Operation

On July 21, 1856, the Illinois Central Railroad started suburban service in Chicago by running four trains each way between down-town Chicago and Hyde Park. It is recorded that the first train to Hyde Park did not carry a single paid passenger.

This service was gradually extended until, in July of 1926, there were in regular operation on each normal week day, a total of 398 trains with service extended to Matteon on the South, to South Chicago on the South Chicago Branch, and to Blue Island on the Blue Island Branch. In the year 1925, this steam service carried a total of 24,000,000 paid passengers. Approximately 285 coaches, mostly of wood construction and with an average seating capacity of 56 persons, were used in this service. About 60 locomotives were necessary for the daily operation.

Electric Operation

Electric operation for the suburban service has been agitated for years by various civic bodies, and the first formal report on feasibility and costs was made in November, 1909. This was followed by several other investigations and reports, but the railroad did not agree to the project until the passage of the so-called Lake Front Ordinance in 1919. This provided that the suburban service should be completely electrified by February 20, 1927. The commitment of the Illinois Central to electrify its tracks in the City of Chicago was a part of its general agreement with the City of Chicago, the South Park Commissioners and the War Department, covering riparian rights, changes in grades to permit of easy access to the lake front, and changes in property ownership.

On July 21, 1926, exactly 70 years after the first steam service was started, three electric trains were operated each way in the local service between Randolph Street and Hyde Park. It will be noted that the electric service was started seven months before the time called for in the Lake Front Ordinance. The second week 80 trains were operated each day and in the period of about five weeks, the electric service was built up to a total of over 350 trains. These were all operated, of course, on the existing steam time-table, as there was still a considerable number of steam trains in the service.

The first electric time-table was put into effect on August 28th, with a total of 396 revenue trains. On account of a shortage of new equipment it was still necessary to run six trains by steam, but these were confined so far as possible to those carrying shop employes.

To-day, 470 revenue trains are being operated on a normal week day. In addition there are 14 equipment trains and 72 Chicago, South Shore, and South

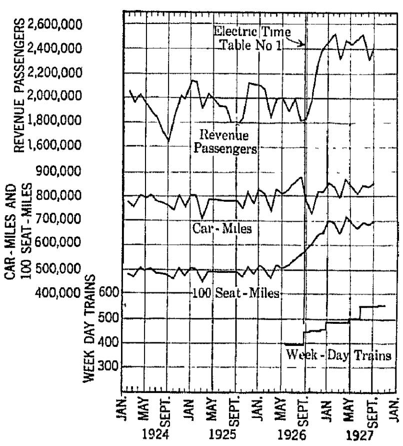

Fig. 1—Operating Curves Before and After Starting Electric Operation on Illinois Central Railroad

These curves show the number of revenue passengers per month, car-miles per month, hundreds of seat-miles per month, and number of week-day trains per day

Bend trains, the latter being operated between Kensington and Randolph Street. This is a total of 556 electric trains.

Electric service was put into effect without any serious accidents or interruptions and has so continued during the first year.

Due to the fact that all of the motor-trailer car units are uniform in design and in operating characteristics, the preparation of time-tables, and the handling of equipment at terminal points has been greatly simplified.

Fig. 1 shows by months the revenue passengers

*For description of Illinois Central Suburban Electrification, see *Journal of Western Society of Engineers*, March, 1926, Vol. 31, No. 3. *General Electric Review*, April, 1927, Vol. 30, No. 4.

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Presented at the Regional Meeting of District No. 5 of the A. I. E. E., Chicago, Ill., Nov. 28-30, 1927.

See pp. 133-135 of Feby 1928 Jnl AIEE

carried, car-miles and seat-miles operated, and the week day trains in service.

Improvement in Service

Of particular interest is the improvement in running times due to electric operation. The latest electric time-table shows decrease in running times over the old steam service of from 11 to 28 per cent for the various classes of trains, the larger percentages resulting for trains to Kensington and beyond. The decrease in over-all time results from high maximum speeds and by the use of high accelerating and braking rates. Acceleration is at the rate of 1½ mi. per hr. per sec., which is about six times as rapid as that of through passenger steam trains. Under normal operation, a train will reach a speed of 28 mi. an hr. in 20 sec. After that point, the rate of acceleration falls off but on level tangent track a train will reach a speed of 50 mi. per. hr. in two minutes. With present average voltage conditions, balancing speed is about 64 mi. per hr. Although comparatively high braking rates have been accomplished on the steam trains, these also have been increased so that electric trains brake at the rate of 1¾ mi. per hr. per sec. It is significant that large decreases have been made in running times even on runs where more stops are made than formerly.

There has been a large gain in electric operation as compared with steam operation from the stand-point of operating a congested terminal. This improvement will become of greater importance as the service grows, inasmuch as under steam operation the limit to the number of trains physically possible to move in or out of the Randolph Street Terminal was rapidly being approached. It is readily apparent that this gain is made by the elimination of movements necessary for steam engines in changing ends of trains, and also in being brought from and taken to the engine terminal, since these movements must be made over the tracks serving useful train movements. The electric train requires only the normal loaded movements over these busy sections, except when brought from or taken to storage tracks at the beginning or end of rush hours.

The speed and reliability of electric service has been further enhanced by other improvements of the entire terminal. These include changes in the grades, rearrangement of tracks, elimination of railroad grade crossings, installation of high platforms at all suburban stations, installment of additional interlocking plants, and rebuilding of the entire automatic block system to conform to electric traction requirements, a great part of which had been completed at the time of beginning electric operation.

Equipment

The results obtained from the motor-trailer combination have been satisfactory to the operating officers. The elimination of all steps on the cars for regular operation which requires high platforms, the use of sliding doors, fully enclosed vestibules, tight lock couplers, automatic acceleration, and electropneumatic braking have all tended to increased convenience of the passengers and to safety and speed of operation.

The employment of a large amount of aluminum or aluminum alloys in side and roof sheets, doors, conduit, and fittings has materially reduced the weight of the cars and, thereby, the operating expense.

For the year ending September 1, 1927, the average cost for maintaining the cars has been about six cents per car-mile. The weight of the motor car is 70.65 tons and the trailer 44.27 tons—an average weight per car of 57.46 tons.

Delays due to electrical equipment have been very few and no radical changes in design have been found necessary. Minor changes incident to new designs have been made, but at very slight expense.

Fig. 2 shows the kw-hr. per car mile with corresponding average temperatures. Electric heating of cars is, of course, largely responsible for the variation between the different months, but changes in time-table also affect it slightly.

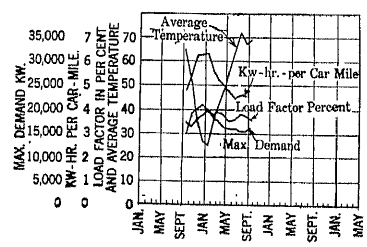


Fig. 2—Curves Showing Monthly Operating Records With Electric Service (Temp. in deg. Fahr.)

These curves show monthly averages of temperature and kw-hr. per car-mile, monthly load factor, and monthly maximum demand.

Power Supply

For the year ending September 1, 1927 the total energy supplied under the contract with the Commonwealth Edison Company was 57,274,512 kw-hr. Of this, 92.7 per cent was for traction purposes including heating of cars, 6.1 per cent for light and power, and 1.2 per cent for signals.

Fig. 2 also shows the maximum demands by months and the variation with the temperature.

The contract provided that the railroad company guarantee a 30 per cent load factor. Fig. 2 shows the variation in the load factor. It will be noted that it is well above the guarantee.

Fig. 3 shows typical summer and winter week day load curves.

The supply of energy by the power company in specified feeders to the right-of-way line of the railroad company from the seven substations has been looked upon from some quarters with misgivings. This requires that not only the conversion machinery but all protective apparatus in the railroad company's feeders be maintained by the power company. The railroad company, however, has taken over, under normal

operation, the control of all traction feeders by use of its supervisory control system.

So far the results obtained have been satisfactory with the power company's broad-minded policy in operating under the necessarily somewhat complicated agreement.

Discrimination of the high-speed circuit breakers has been excellent. The overhead network on a multiple track railroad such as this installation covers is complex due to a necessity, in case of a fault, of having a minimum amount of track out of service. Isolation of individual sections in case of trouble has come up to expectations with very good protection to line and equipment. Furthermore, the power supervisor controlling the traction feeders has immediate information as to opening of breakers. He is located in the office of the train dispatcher, so that by working close together, trouble from a train going from a live to a grounded dead section has been minimized. The use of wayside signals indicating a dead trolley section at points where the sectioning is outside the limits of interlocking plants has also saved burn-outs of overhead.

The cold weather of the first winter indicated that a few minor changes, especially in pull-offs, were desirable. The delays which have occurred, however, have been small considering the size of the installation and the number of trains operated.

General Results

As indicated on Fig. 1, it is apparent that the traveling public will use a clean, fast, and reliable transportation system. The off-peak business has increased

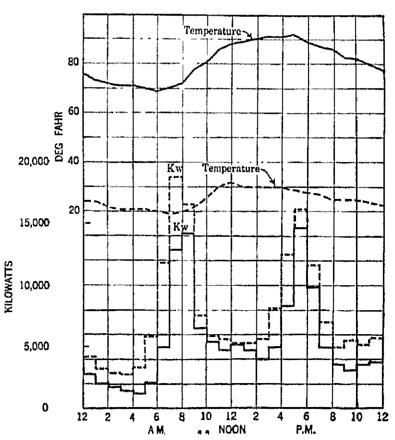


Fig. 3—Typical Summer and Winter Week-Day Load Curves and Temperatures

Full lines are for typical summer day, July 27, 1927 (time table No. 5). Dotted lines are for typical winter week-day curve, January 25, 1927 (time table No. 4).

materially, which, of course, is the most satisfactory business to have.

As announced in the newspapers recently, the operating income is now on the right side with an indicated profit of about $530,000 for the year 1927 as against a loss for the year 1926 although the electric service was in operation four complete months during that year. It is pointed out, however, that these figures do not take into account any investment in road and equipment. In providing the electrified service the railroad spent ten and one-half millions of dollars for new equipment, about four

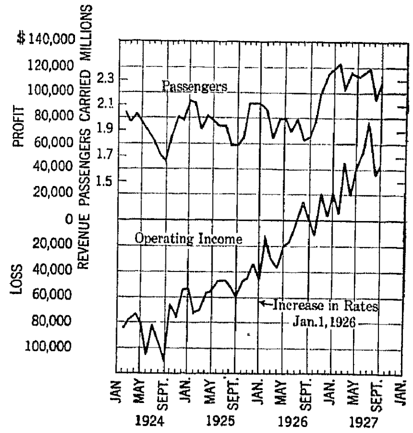


Fig. 4—Curves Showing, Monthly Net Operating Income and Number of Passengers Carried per Month

Figures for Illinois Central suburban service including Chicago, South Shore, and South Bend Railroads

millions for electrical work, including overhead, switching equipment, return system and miscellaneous, and about nine and a half millions for rearrangement of old tracks, new track and station facilities and separation of grades, or a total of twenty-four millions in improvements only. An additional twenty millions of dollars was spent in the rearrangement of the terminal facilities for the whole electrification project.

Fig. 4 shows the relation between operating income and passengers carried for the three and one-half years.

Discussion

A. M. Garrett: I want to mention the operation of the high-speed breakers which are installed upon the feeders.

For a short time after the electric railway system was placed in service, we experienced as many as 400 to 500 openings per month of the feeder breakers in a substation. During this period none of the breakers in any of the substations failed to operate properly, which shows exceptionally good performance.

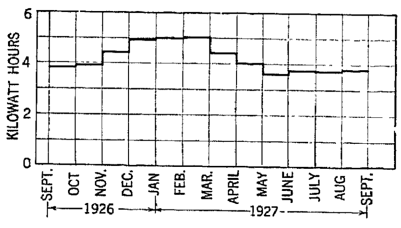
A. J. Klatte: The achievement that the Illinois Central has made in turning a loss to a profit is the most outstanding feature of the entire year's efforts.

A remarkable feature of the whole thing is the frankness of the details of the contract between the Illinois Central and the power distributing company here in Chicago. The statement that the power company met all of the Illinois Central's difficulties of operation and cooperated fully, is heartily endorsed by the experience we have had here in Chicago.

To my surprise instead of losing revenue as a result of this electrification, the Chicago surface lines have had an increase in the number of revenue passengers on every line adjacent to or crossing the Illinois Central.

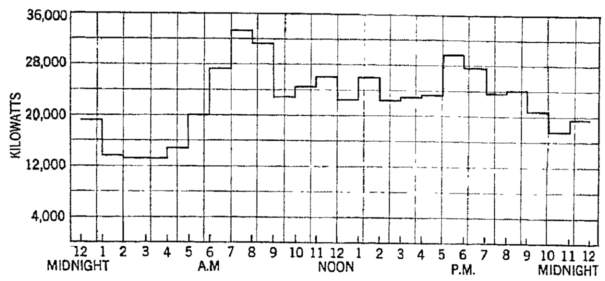
Sidney Withington: (communicated after adjournment) The figures indicating approximately 4.6 to 6.4 kw-hr. per car-mile are among those which are of especial interest. It is understood, however, that they represent power measured at the substations, and therefore include distribution losses. It would be of

interest to have the power consumption measured at the pantograph. The seasonal variation is of course a function of journal friction as well as of car heating. The power consumption figures on the New Haven are presented herewith by months, and run from approximately 4.0 to 5.7 kw-hr. per car-mile measured at the pantograph on the a-c. zone. Adding, however, transmission and distribution losses, these figures would be about 4.2 to 6.0 respectively. It is of course true that the power consumption is a function of frequency of stops, rate of acceleration, as well as weight of cars, grades, etc., and no comparison should be made without taking these conditions into consideration.



K. W. H. Per Car Mile.

The power curves which Mr. Vandersluis presents indicate clearly the advantages which would accrue if electrification included yard switching and freight and through-passenger operation in addition to suburban service. The valleys during the middle of the day and at night would be largely filled up, and the load factor correspondingly improved. A typical daily load curve for winter and summer on the "New Haven" is presented herewith as a comparison. The load factor improvements, of course, would apply not only to power supply but also to substations and distribution facilities, and these improvements obviously would make an important difference in the capital or overhead and other fixed charges.

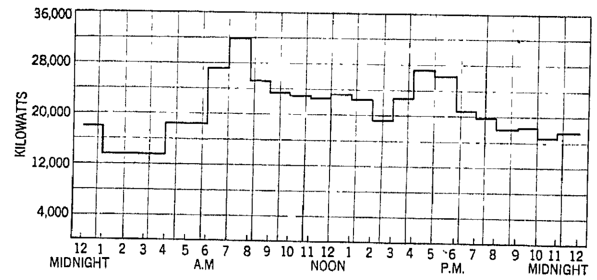


Load Curve for a Typical Winter Day

The cost of maintenance per car-mile of 6 cents may be compared with a cost on the New Haven of approximately 4.5 cents, which includes complication caused by dual a-c./d-c. apparatus, a feature of New Haven equipment on account of operation over the third rail of the New York Central tracks. It is possible that the Illinois Central figures include items not included in the New Haven figures. It seems probable that the first year of operation would provide somewhat less maintenance costs than subsequent operation as the cars grow older and more replacements are required on account of wear. On the other hand, there may be some extra expense during the first year's operation on account of a new organization or in correcting minor defects.

A comparison of ratio of weight and nominal hp. of the motor cars and trailers is of interest. The normal two-car operation of the Illinois Central with 71 tons on the motor car and 44 on the trailer gives a total of 114 tons per pair of cars. This, correlated with the nominal horse power of the four motors at 250 hp. (it is presumed this is continuous rating) gives a figure of .114 tons per hp. The New Haven multiple-unit cars operated nominally with one motor car at 88 tons to two trailers at 52 tons each, comprise a combined weight for the three cars of 192 tons. The nominal continuous rated capacity of New Haven motors is 150 hp., and the aggregate motor capacity for each three cars is therefore 600 hp. The ratio of weight to rated hp. is therefore 0.32, or about three times that on the Illinois Central. It is true that on account of make-up of trains it is not possible on the New Haven always to operate on a ratio of one motor car to two trailers, but the actual operation is not far from this figure.

The above comparison, of course, does not by any means necessarily represent actual load conditions on the motors, as the load depends on the frequency of stops, rate of acceleration



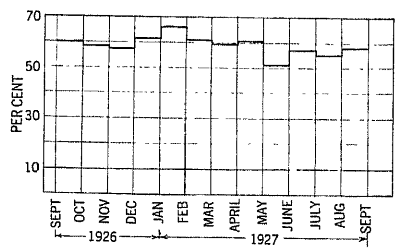
Load Curve for a Typical Summer Day

(relatively high on the Illinois Central), speed, grades, and many other factors which can be considered only in a lengthy analysis.

The figure of $4,000,000 for electrical work, including overhead, switching equipment, bonding, etc., but presumably not including substations, seems somewhat high, but it is understood to include a number of facilities which are designed for the ultimate electrification and a number of items not directly chargeable to electrification, such as signal and station lighting facilities, and it is thus hardly fair to consider it as a figure for "electrification" or to assume the fixed charges as a burden on the electrification.

It is emphasized that the returns on any given electrification project are largely dependent upon the "factor of use" or load factor of each item, not only of power supply, but of transmission facilities, substations, distribution system, etc.; and the full benefit cannot usually be realized until all classes of service on a given project are electrically operated. When this occurs on the Illinois Central, it seems entirely likely that the returns will more than pay the fixed charges on the installation.

It is hoped that Mr. Vandersluis' presentation will stimulate other railroads to present operating figures for comparison, although it must be constantly kept in mind that a great deal of careful analysis is necessary in utilizing such figures to insure that they are on a strictly comparable basis.



System Load Factor

W. M. Vandersluis: In connection with Mr. Klatte's remarks, I wish to emphasize the fact that while the operating revenue has increased, yet the Illinois Central is a long way from making any money on account of the electrification of its suburban service. The operating accounts do not include any interest on the investment.

Mr. Withington compares the tons per hp. of the New Haven equipment with the Illinois Central, using the 250-hp. nominal rating of the motors as the continuous rating. The figure of 250-hp. per motor is the one-hour rating. The ratio of weight to rated hp. is 0.1675 instead of 0.1140 mentioned by Mr. Withington.

120-Ton Storage-Battery Locomotive
Performance in Chicago Terminal Freight Yards

BY EDWARD TAYLOR[1]

Synopsis.—*This paper describes the design and performance of a 120-ton storage-battery-driven locomotive which has been in switching service in the freight yards of the Chicago railroad terminals. It shows that this locomotive has many advantages for this service including absence of smoke, quietness, a high factor of availability, ease of control, and economy.*

RAILWAY yard switching in metropolitan areas involves problems and limitations not met with in less densely settled districts. In Chicago it has seemed desirable to lessen the smoke produced in these yards and electrification of the tracks in the yards has been suggested as a remedy. Complete electrification however presents many difficulties, both physical and economic.

After considerable study it appeared that a combination system of electrification of some of the tracks and use of storage-battery-operated locomotives would go far to solve this problem. It was therefore decided to design and construct a storage-battery yard-switching locomotive and to test it under operating conditions in order to determine its practical and economic possibilities.

This locomotive has now been in service over a year

FIG. 1—STORAGE-BATTERY LOCOMOTIVE

in several switching yards in Chicago. Its performance records, which are reported in this paper, show that it has many advantages. A summary of the results of the tests is as follows:

I. With one charge (616 kw-hr. capacity) it will do the following:

(a) Make 340 runs of 0.119 mi. including acceleration, with a trailing load of 306 tons, (5 61-ton cars) at an average speed of 5.4 mi. per hr. over a period of 12.5 hr., which allows 60 per cent for actual running time. See Fig. 7.

(b) Haul a 306-ton trailing train (5 61-ton cars) ½ mi. including acceleration, and make 101 such moves at a balanced speed of 17 mi. per hr.

(c) Haul a 500-ton train (8 62½-ton cars) at 16 mi. per hr., taking 6 lb. per ton for traction, at an hourly output from the battery of 147 kw-hr., and will continue to haul it for 4.2 hr.; or it will haul the 500-ton trailing train for 67 mi., or 33,500 trailing ton-miles.

(d) It can do 12 hr. of the average yard-switching service of all the railroads in Chicago on one charge and can be recharged in six hours. This locomotive is equipped with a socket for charging from central station off-peak power at relatively cheap rates.

II. It can exert a tractive effort of 60,000 lb. at 3 mi. per hr. It is controlled handily and smoothly, has a high factor of availability, requiring a minimum of time for getting ready, and a minimum of attention when not operating.

III. It can readily be equipped with a 25- or 60-cycle motor coupled to the present generator, and in connection with a pantograph, collect its replacing charge if desired from a simple trolley carried over a convenient track and thereby be available for service 24 hr. a day.

IV. It operates quietly, without smoke, noxious gases, or steam and is a handy tool for the work of terminal switching and sounds a new note in motive power for congested terminals.

V. Its operation is more economical than steam and it may be a preliminary step to a progressive electrification if desired.

Yard-switching data which could be used in designing the locomotive were somewhat meager and conflicting as would be expected from the radical differences in operating conditions in the various yards. The following, however, represent average typical switching conditions with steam locomotives in the Chicago yards. These data are given in the Smoke Abatement Report of the City of Chicago.

Average weight train incl. locomotives	425 tons
" length all switching moves	628 ft.
" distance traveled by locomotive in one 8-hr. shift	26 mi.
" speed while in motion	5.4 mi. per hr.
" ton-mi. for steam locomotive on usual two 8-hr. shifts per day	22,000 ton-mi.
Proportion of time in motion while assigned	60%
Coal consumed per hr	0.37 tons

After considering all available data a locomotive was built with the following specifications:

1. General Electric Co., Chicago, Ill.

Presented at Regional Meeting of District No. 5 of the A. I. E. E., Chicago, Ill., Nov. 28-30, 1927.

GENERAL DESCRIPTION STORAGE-BATTERY LOCOMOTIVE NO. 10036

Dimensions:

	Ft.	In.
Total height	14	6½
Width over rain guard	10	3
Width over grab handles	10	7⅜
Length over sill	49	0½
Truck centers	31	0
Length over face of couplers	52	0
Rigid wheel base	8	0

Weight:

Locomotive complete.......237,000 lb.
Storage Battery.......78,960 lb.

Performance:

Tractive effort 6 mi. per hr.......39,200 lb.
" " 12 " " ".......14,700 lb.
Locomotive horse power.......800 hp.
Maximum tractive effort at 30% coefficient of adhesion.......71,000 lb.
Maximum speed, light.......30 mi. per hr.

Equipment:

4 GE-287 motors, 200 hp. at 300 volts each, with forced ventilation, gear reduction 66/16; 39 in. wheels.
1 Winton gas engine, Model 106-A-220 hp. 1000 rev. per min., 6-cylinder, 7¼ by 8 in. cylinders, direct-connected to DT-509-A 135-kw. shunt-wound 230-volt generator. Radiator for engine is blown. Capacity of gas tank 150 gal.
1 Storage battery "Exide Ironclad"—120 cells FL-31, 2700 ampere-hr. capacity at 230 volts, or 616 kw-hr.
1 PCL control—20 points, including tap field.
1 CP-26, 100-cu. ft. compressor. Straight and automatic air brakes.
ARA draft gear with 5 by 7-in. shank.

The battery chosen for this locomotive is of a type developed for submarine service where the highest quality is essential. This type was selected after an extended investigation had proved that this type was best suited for the kind of operation for which this locomotive was designed. A battery with low internal resistance is desirable, permitting high discharge with low drop in voltage, because a locomotive of this type is inherently a heavy-duty low-load-factor machine.

The characteristics of the battery, motors, charging generator, and entire locomotive are given in Figs. 2 to 7.

The battery consists of 120 cells having a tota weight of 40 tons. This weight is placed half on each of the two locomotive trucks, and as as every locomotive wheel is a driver it might be said that the locomotive tender has been placed on the drivers. In contrasting this tender with that of a steam locomotive, a very great difference is evident, for whereas the coal for the steam locomotive must be fired to generate steam for the cylinders, the power from the electric tender is available to the traction motors instantly and in such quantities as is required by the work. The normal battery rating is 450 amperes for 6 hr. Due to the high-discharge-rate characteristics of this battery a current of 28 times this amount can be drawn from the battery for short periods. The weight of batteries on drivers, giving greater than normal track adhesion, can be utilized thus for occasionally doing work which would be beyond the normal rating of this locomotive.

A storage battery may be considered a potential

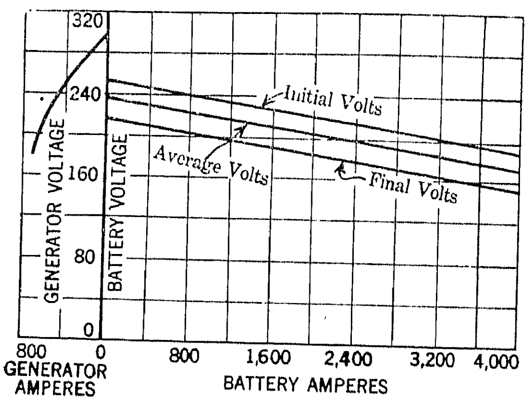


Fig. 2—Characteristic Curves of Storage Battery and Generator

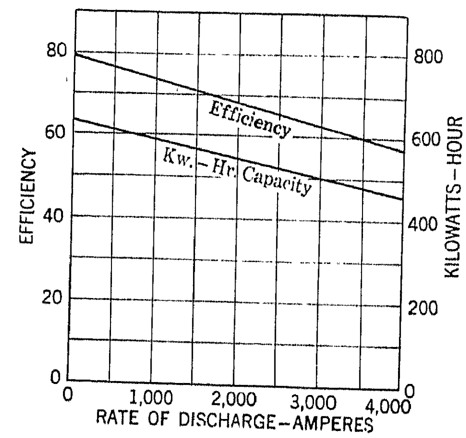


Fig. 3—Approximate Efficiency of Battery and Kw-Hr. Capacity at Various Rates of Discharge

The efficiency is at the battery terminals and is the ratio of kw-hr. output to kw-hr. input. It is based on: (a) charging the battery in approximately 6 hr., (b) discharging intermittently so that its full ampere-hr. capacity is utilized

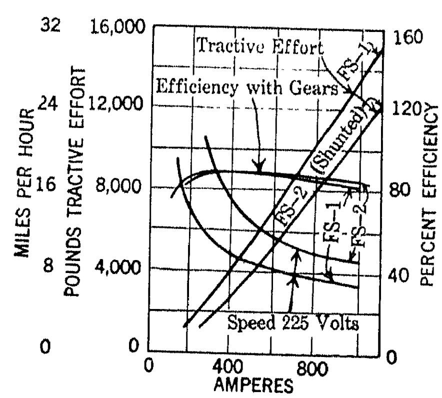


Fig. 4—Characteristic of Motor Used on Locomotive

Operated at 225 volts. Gear, 66 teeth. Pionion, 16 teeth. Wheel diameter 39 in.

source of power containing a very definite amount of energy, in this case 616 kw-hr. or 821 hp-hr. This power is available for use at any instant, at any rate

from 100 amperes which could be used continuously for 27 hr., to 6000 amperes for short-time operation. In order to get the best service from a battery locomotive its characteristics should be taken advantage

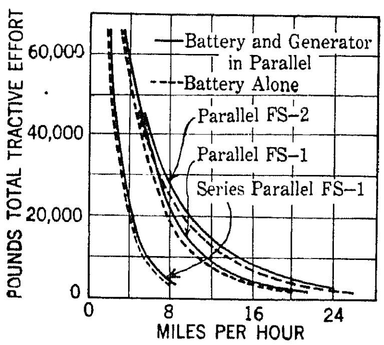


FIG. 5—TRACTIVE EFFORT DEVELOPED BY STORAGE-BATTERY LOCOMOTIVE

of; that is, its assignments should be of such a nature that the average work to be done, including all heavy drags and all stops, allows the batteries to hold up for a

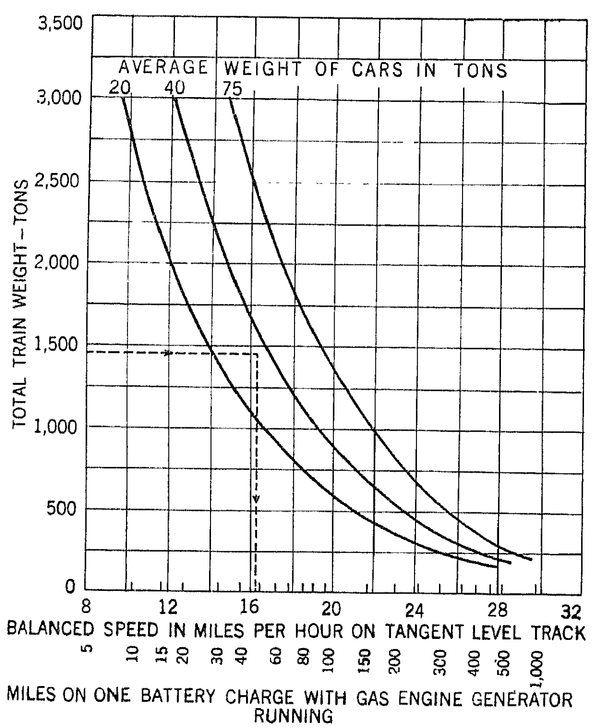


FIG. 6—PERFORMANCE OF STORAGE BATTERY LOCOMOTIVE ON CONTINUOUS FREIGHT-TRAIN RUNS

Train resistance assumed to be as shown in Bulletin No. 43 of the University of Illinois Experimental Station (Professor Schmidt). Locomotive operating in full parallel position with shunted field and with gas-engine generator in parallel with battery

reasonable length of time. For instance with the present battery on a 16-hr. job the average rate of work should not exceed 38 kw-hr. per hour, and on an 8-hr. job should not exceed 77 kw-hr. per hour unless means are provided for recharging the batteries while working.

As between batteries of the same construction the life of each depends primarily upon time and temperature. That is, a battery which is used within its discharge rating and thereby is not allowed to attain too high a temperature, will have a much longer life than one which is habitually overloaded. The battery on this locomotive is large enough for the other equipment so that in the service for which the locomotive was designed it is operated well within its rating. Therefore, it is expected to give more than the four years service nominally considered its life.

Each of the 120 cells in this battery consists of a

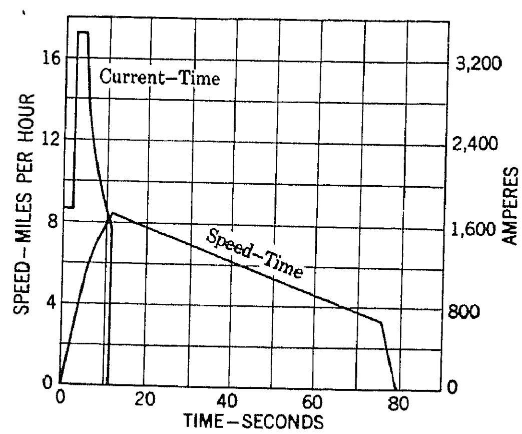


FIG. 7—CHARACTERISTIC CURVES OF AVERAGE RUN IN YARD-SWITHCING SERVICE IN CHICAGO TERMINALS

These curves correspond to the average run as shown in Table I.

The 120-ton storage battery will haul this average trailing load the same distance with the same average running speed as the steam locomotive, and, providing its running time is 60 per cent of the total time, will continue to do this service for 12.5 hr. on one battery discharge, without use of auxiliary gas engine, making a total of 340 runs.

To do this requires that each run be of the character shown by the speed-time curve above. The initial rate of acceleration is 1.0 mi. per hr. per sec., corresponding to 19 per cent adhesion and 860 amperes per motor during the period of notching up the controller. Power is shut off at 8.4 mi. per hr. and the train coasts down to 3.3 mi. per hr., with a retardation rate of 0.08 mi. per hr. per sec., after which the train is braked to a stop at the rate of 0.87 mi. per hr. per sec. Total time of run 79.3 sec., distance covered 0.119 mi., average speed 5.4 mi. per hr., trailing load 306 tons, total load 426 tons.

It is anticipated that under service conditions less coasting and a lower initial rate of acceleration will be desirable, giving the same average running speed. This will require more power for each typical run and the time of operation for one battery discharge may be brought down to 8 hr., with a total of 218 runs.

rubber jar containing the plates and electrolyte. Each jar rests in a wooden tray as high as the cell itself and provided with crane eyes for hoisting the cell from its main compartment in the locomotive. Each jar is insulated from each adjacent one and from the compartment floor with porcelain insulators. To replace a cell it is necessary only to unbolt the copper connection straps and raise the cell.

About once a month replenishing water is needed to compensate for evaporation. Ordinary hydrant water is used for this purpose. This filling and an occasional overcharge to equalize the condition of the cells are

all the attention which the battery requires. This is the extent of work done on the locomotive storage batteries during eight months of switching service on six Chicago railroads.

Operators are at times reluctant to use a storage battery for heavy haulage work as many features of its operation and costs are not fully understood. Steam railroads, however, should not be deterred from applying it as they are large users of batteries for car lighting, signal, and other purposes.

Different railroad terminals will have local limitations, restricting their choice of motive power over a wide range; for instance, the yards operated in these tests varied over 20 to 120 kw-hr. per hr. and length of duty from one 8-hr. shift to two 8-hr. shifts as necessary, and it appeared desirable to have continuous 24-hr. operation per day in service. This last is only possible where there is some overhead or third-rail contact.

Service Records

This storage-battery locomotive, fully equipped with instruments, was completed on October 26, 1926, and run to Chicago on its own power hauling a 60-ton coach at a mean speed of 32 mi. per hr. On arriving in Chicago it was turned over in turn to each of six of the class "I" roads for service tests and trials, displacing in each case the usual steam locomotive. No restrictions were placed on its service except to point out that it was a switcher rather than a road locomotive.

On account of the various types of locomotives used and the methods of operating the locomotives, it seemed advisable to investigate several systems so that a fair mean duty could be arrived at, and the following tabulations are the results of service operation under the wide variety of conditions that exist in the different yards.

Operation in Wood Street Yards

While this locomotive was in service in October and November 1926 in the Wood Street yards, it was assigned to the various jobs ordinarily performed by 90- and 120-ton (weight on drivers) steam locomotives.

Kind of work	No. of days, total	Kw.hr. used by loco., total	Assigned wkg. hours, total	Miles of oper. total	Av. kw. used by loco. during wkg. hrs. incl. all stops: Av. per day	Av. for hardest day	Av. mi. per hr. during wkg. hrs. incl. all stops: Av. per day	Av. for hardest day
Heavy switching	3	1660	20	62	119	151	3.1	3.7
Pulling freight	4	2080	24.5	115	122	181	4.7	5.8
Roustabout	7	3280	58.5	207	81	104	3.5	3.3
Booster	1	450	7	26	92	92	3.7	3.7
Break up	4	2460	34.5	127	102	125	3.7	4.2
Pass. terminal (days)	4	1775	34	188	75	91	5.5	7.4
Pass. terminal (nights)	3	728	24	78	43	49	3.2	2.5

The preceding tabulation is a summary which is of interest in showing the actual power required for these jobs.

During the four days of passenger-terminal work the records showed a power consumption averaging 70.6 watt-hr. per gross ton-mi.

The movements of the locomotive from the battery-charging station and return are included in the above tabulation. The total trailing ton-mi. handled during the four days was 16,863.

In Jackson Street Yard

During December 1926, this locomotive was in service principally in the yards north of Congress Street. The kind of work may be classified under two headings as shown with the length of time in each service.

Freight switching (8 days of 16 hr. each)

Baggage switching in the passenger terminal yards (2 days of 16 hr. each)

Operating data is as follows:

	Freight Switching	Baggage Switching
Locomotive-mi. per 16-hr. day	38.2	33.0
Trailing ton-mi. " " "	13960	5000
Average trailing load	360	151
" gross load	480	271
" length of movement (ft.)	517	356
" speed while in motion (mi. per hr.)	6.7	4.7
" speed including all stops	2.4	2.1
" speed including all stops on hardest day	2.9	2.0
Per cent standing time	64.5	56.5
Kw-hr. used by locomotive per 16-hr. day	1140	783
Average kw	71.5	49.0
" kw. on hardest day	85.6	49.8
Watt-hr. per gross ton-mile	61.5	86.5

During this period the electric locomotive operated in regular yard service and performed successfully in comparison with the regular 70-ton six-wheel steam switching locomotives. In fact on some unusually cold days it was one of the few locomotives in the yards doing its full quota of work.

Operation January 19 to February 2, 1927

Classification Yard No. 1. The storage-battery locomotive was used in heavy classification switching and did the work which is ordinarily done by a 95-ton (on drivers) steam locomotive.

Coach Yard. The work consisted of hauling main-line passenger trains to and from a "Y" point for turning, and miscellaneous switching in a passenger-coach yard. The steam locomotive ordinarily used in this work weighs 64 tons on drivers.

Union Depot. This work consisted of switching express and mail cars in and about the main passenger terminal. The battery locomotive in this service replaced a 64-ton (on drivers) steam locomotive.

Kinzie Street Yard. Industrial switching. The 64-

ton-on-drivers steam locomotive is ordinarily used in this work.

SUMMARY OF TEST RESULTS

Jan. 19 to Feb. 2, 1927

	Classification Yard No. 1	Coach Yard	Union Depot	Kinzie Street Yard
(a) No. of days under test....	3	1	4	3
(b) Total hr. and min. in service................	23–25	7–38	28–26	22–11
(c) Total mi., light..........	17.3	16.1	33.1	20.1
(d) Total mi., loaded........	55.7	22.3	70.4	31.2
(e) Total mileage ($c + d$) ...	73 0	38.4	103.5	51.3
(f) Mi. per day ($e \div a$)......	24.3	38.4	25.9	17.1
(g) Ave. mi. per hr. in service.	3.11	5.03	3.64	2.32
(h) Ave. mi. per hr. while in motion...............	4.70	8.53	7.56	4.10
(i) Per cent time in motion (100 g/h)...........	66.4	59.2	48.4	56.6
(j) Total no. of cars handled.	966	56	427	507
(k) Total gross ton-mi.......	33,413	20,351	28,518	13,004
(l) Ton-mi. per day (k/a)....	11,138	20,351	7,129	4,335
(m) Total kw-hr. used........	2,640	692	1,484	1,230
(n) Watt-hr. per gross ton-mile (1000 m/k).......	79.2	34	52.1	94.7
(o) Ave. kw. in service (m/b).	104	91	52	55
(p) Hr. on one battery charge (616/o)...............	5.9	6.8	11.8	11.2

Operation in LaSalle Street Terminal

On March 26, 1927 the storage-battery locomotive took over for three weeks the assignment of one of the six-wheel steam switching locomotives in the LaSalle St. passenger station.

The work of the switching locomotives in this terminal consists of running in after incoming trains, pulling the cars out to relieve the inbound locomotives and placing the cars on other tracks ready for outbound service or spotting them on express or mail tracks. Trains are also split up and rearranged, and cars put on storage tracks. This switching occupies mainline track and must be done without interfering with the 150 scheduled daily train movements.

The storage-battery locomotive handled this work from March 29 to April 1 very satisfactorily. A summary of the averages obtained from a three-day test in this service is as follows:

	Average per Day
Number of moves................................	82
Hr. on duty....................................	7.8
Mileage while working..........................	25.9
Mileage of locomotive light....................	9.1
Number of cars moved...........................	177
Kw-hr. used....................................	461
Per cent time standing.........................	40
Mi. per hr. including all stops................	3.3
Length of average moment in ft.................	1670
Total trailing ton-mi..........................	3014
Average trailing tons..........................	116
Gross ton-mi. per hr...........................	785
Average kw.....................................	59
Kw-hr. per locomotive-mi.......................	17.8
Watthours per gross ton-mi.....................	75.3
Hr. for complete discharge of battery..........	10.4

DATA FROM 22 DAYS OF OPERATION INCLUDING THE 3 DAYS ABOVE

	Average Day	Hardest day
Hr. on duty.........................	8.6	8.7
Mileage while working...............	28	31
Kw-hr used..........................	490	600
Mi. per hr. including all stops.........	3.3	3.6
Ave. kw-hr..........................	57	69
Hr. for complete discharge of battery...	10.8	8.9

Operation in Kinzie Street Yard

On February 15, 1927 a complete record was made of a typical day's work of freight terminal yard switching in the Kinzie Street Yard. The following is a summary of this day's work:

Locomotive-mi. from roundhouse to Kinzie St. yard and return........................	6.67
Light locomotive-mi. in Kinzie St. Yard........	6.50
Loaded locomotive-mi. in Kinzie St. Yard......	12.73
Total locomotive-mi.....................	25.90
Total time in Kinzie St. Yard................	9 hr. 57 min.
Percentage of this time standing..............	54
" " " " in motion.............	46
Locomotive ton-mi. while in Kinzie St. Yard....	2327
Trailing ton-mi.............................	2893
Total ton-mi. in yard....................	5220
Battery discharge while in yard, kw-hr........	428
Average kw. in yard.........................	42.9
Average kw-hr. per locomotive-mi. in yard.....	22.2
Average watt-hr. per total ton-mi. in yard.....	82.1
Average mi. per hr..........................	1.94
Average mi. per hr. while in motion...........	4.22

SUMMARY OF STORAGE-BATTERY AND STEAM LOCOMOTIVE TESTS FOR 6 DAYS IN CORWITH YARD, MAY 1927

Storage-Battery Locomotive No. 10035	Average per day
Total weight...........120 tons	
Weight on drivers......120 "	
Hr. on duty............................	7.4
Number of moves........................	278
Total mileage on duty..................	26.4
Light locomotive mileage...............	7.7
Number of loaded cars moved............	897
Number of empty cars moved............	552
Length of average movement in ft........	512
Mi. per hr. including all stops............	3.5
Total trailing ton-mi..................	6027
Average trailing load in tons............	224
Gross ton-mi. per hr....................	1241
Kw-hr. used............................	584
Average kw.............................	79
Kw-hr. per locomotive-mi................	22.0
Watt-hr. per gross ton-mi................	64.3
Hr. for complete discharge of battery......	7.9

Steam Locomotive No. 2084 (3-day test)	Average per day
Total weight..........126 tons	
Total weight on drivers. 77 "	
Hr. on duty............................	7.4
Number of moves........................	295
Total mileage on duty..................	27.2
Light locomotive mileage...............	5.8
Number of loaded cars moved............	1045
Number of empty cars moved............	593
Length of average movement in ft........	485
Mi. per hr. including all stops............	3.6
Total trailing ton-mi..................	5190
Average trailing load in tons............	191
Gross ton-mi. per hr....................	1160
Lb. of coal used (incl. firing up)..........	8300
Gal. of water used......................	3730
Lb. of coal per hr......................	970
Lb. of coal per locomotive-mi............	268
Lb. of coal per gross ton-mi..............	.85

SUMMARY OF TEST RESULTS
STORAGE BATTERY LOCOMOTIVE
May 25, to June 1, 1927

	Average Per Day Bellewood Yards	48th Ave. Yards	Lincoln St. Yards
Number of movements	114	139	84
Hr. in motion	5.5	5.2	3.84
Hr. standing	2 9	2.3	4.18
Hr. on duty	8.4	7.5	8.02
Total locomotive-mi	37 9	32.2	24.2
Light locomotive-mi	4.8	9.0	9.6
Total number of cars moved	745	979	153
Kw-hr. used	772	681	338.8
Per cent time standing	34.5	30 7	52.1
Mi. per hr. while in motion	6.9	6 2	6.3
Mi. per hr. including all stops	4.5	4.3	3.0
Total distance traveled in ft	200,112	170,016	127,776
Length of average movement in ft	1,755	1,223	1,521
Total trailing ton-mi	11,519	7,906	2,154
Average trailing tons	304	245	89
Locomotive ton-mi	4,548	3,864	2,904
Gross ton-mi	16,067	11,770	5,058
Gross ton-mi. per hr	1,924	1,570	631
Average kw	91 8	90.8	42.3
Kw-hr. per locomotive-mi	20.4	21 2	14.0
Watt-hr. per gross ton-mi	49.0	57.9	67
Hr. for complete discharge of battery	6 7	6.8	14 5

Character of Work

Bellewood Yards, 2 days—Transfer and industrial switching

48th Ave. Yards, 2 days—Heavy classification switching

Lincoln St. Yards, 2 days—Passenger-coach switching.

Conclusions From Tests

From the results of the operating records it was concluded that the storage-battery locomotive offers many advantages in metropolitan yard switching. It has demonstrated that it compares very favorably with the steam locomotive.

In general within the capacity of its battery charge it performs more promtly than its steam counterpart. The engine operates quietly and without smoke, cinders, noxious gases, or steam. Particularly in cold weather this means better vision and a consequent saving of time and reduction of accidents.

It is controlled more easily. For the same weight on the drivers the electric locomotive can accelerate a given load more rapidly than the steam by virtue of its more continuous torque. This permits working on the average nearer the slipping point of the wheels. In addition the absence of the tender weight permits either the handling of additional useful load or more rapid acceleration with the same load. These time considerations indicate that more work can be done per engine. In emergency it can be used at considerable distance from its regular yard.

It has a very high factor of availability requiring a minimum of time for getting ready and a minimum of attention when not operating. The power from the batteries is available instantly and in such quantities as required by the work. It does not have to be repaired as frequently as the steam locomotive. It can be kept continually working at the yards, thus saving crew time in going to and from the roundhouse and relieving mainline track of some non-revenue traffic. It can be charged at a station installed adjacent to a convenient siding in the yard where it ordinarily works. The necessity for charging of course limits the number of hours per day during which the locomotive can be used.

If advantage is taken of idle time, such as lunch hours or periods when there is no work, the locomotive can be operating about 20 hr. per day as compared with 16 hr. maximum for the steam switcher. In many cases however, the electric locomotive can be worked on electrified tracks during part of the time (the off-peak period). In this case 24-hr. service may be made available by adapting the locomotive to collect energy from the trolley or third rail. The trolley energy may be used to drive a motor which drives the present generator, thus keeping the battery charged even under continuous operation. It has low maintenance costs.

From published records of the Interstate Commerce Commission it is obvious that maintenance costs of an electric locomotive are one-third to one-quarter those of an equivalent steam locomotive. The operating costs should of course include the expense of replacing the storage battery at the end of the operating life of the cells. The number of men in a yard-switching crew is fixed so that comparison need include only the charges for maintenance of the apparatus and the interest in the investment. The necessary auxiliary appurtenances are low in number.

Coal and water are not needed nor are turntables required since the locomotive may be controlled from either end. Roundhouse space is not so necessary as the locomotive may be kept out of doors summer and winter.

For charging the battery, advantage should be taken of the low off-peak rates of central-station electric companies. The possible yearly kw-hr. are very high, making the load desirable to a central station. The instantaneous and 15-min. peaks are high, which makes the load undesirable for small power stations but the large power company will not be troubled by them especially in off-peak periods. These periods aggregate 12 to 16 hr. per day and rates as low as one cent per kw-hr. may be obtained in some instances. At this rate, considering over-all efficiency, the actual power cost of the locomotive drivers will be about 1.09 cents per hp. hr. When the combination trolley and battery locomotive is used perhaps a certain rate should be charged while operating on the trolley and a separate rate for off-peak power metered separately to the battery.

In conclusion, this storage-battery locomotive not

only meets smoke-abatement measures and provides a simple effective tool for yard switching which can be installed quickly without extensive preparations, but it lends itself readily to existing electrifications and fits in excellently with future electrifications. If main-line tracks are already electrified, the battery-type locomotive can be equipped with a trolley or pantograph and be charged directly from the existing distribution system while working, and can work 24 hr. per day with few if any additions to the distribution system. On non-electrified systems, when it becomes advisable to put in a straight electric type where the battery locomotive has been working, the latter is relieved for duty in other yards and thus a complete electrification can be built up with the development of the community without the necessity of great expenditure at any one time.

Discussion

(Taylor)

Chicago, Ill., November 30, 1927

B. J. Arnold: The question of various types of locomotives for railroad service is very important at the present time. The gas-electric engine or the Diesel-electric engine for switching service is shown to be the most efficient at the present time. For long, swift work the direct-geared engine outstrips the gasoline-electric combination. The steam engine is making an advance in the triple-expansion engines for marine work. The Diesel engine exceeds that efficiency today, yet the steam engine is keeping pace with the progress of other developments.

H. H. Field: I should like to know more about the battery voltage and the motor connections.

Edward Taylor: The storage battery on the locomotive is conveniently rated at 230 volts. Batteries of this type are usually rated at their 6-hr. discharge rate and the voltage per cell decreases toward the end of the discharge. Also the voltage per cell decreases as the rate of discharge is increased so that it may be said that the discharge voltage per cell depends on the rate of current discharge, the state of charge, the age of the cell, and to a certain extent on temperature.

The 230-volt motors are equipped with control for connecting, first, two motors in pairs for series-parallel operation, then all four in parallel.

Current could be collected at convenient locations from a trolley or third rail and in this case the number of cells used would be selected to conform to the most desirable charging voltage per cell.

Operation and Performance of Mercury Arc Rectifier on the Chicago, North Shore, and Milwaukee Railroad Company

BY CAESAR ANTONIONO[1]

Associate, A. I. E. E.

Synopsis.—*Actual operating results and experiences with a mercury arc rectifier feeding a railroad are given in this paper. The rectifier is compared with synchronous converters in regard to efficiency, troubles, maintenance, and other points.*

THE application of the mercury arc rectifier is one of the newest developments in the railway power field and very little is yet known about its possibilities and applications in this country.

Other papers presented before the Institute have covered the technical points and details on the subject, so that I shall attempt to confine myself to the rectifier's performance on railway work in conjunction with automatic operation.

The development of the rectifier in this country is very much in its infancy as regards its commercial application. It appears to be used more extensively in Europe, and the extent to which it will be applied here is limited only by the economical and operating results which can be obtained.

In considering its application to any property we naturally compare it with the synchronous converter and motor-generator set designed to serve the same class of service, with which we are familiar.

The advantages of the mercury arc rectifier over the synchronous converter and motor-generator according to previous papers presented before the Institute are:

1. High efficiency over the whole working range,
2. Very high capacity to absorb momentary loads,
3. Insensibility to short circuits,
4. No synchronizing,
5. Simple operation and minimum attention,
6. Noiseless operation and no vibration,
7. Low maintenance cost,
8. Reliability of service.

This paper discusses each of these points in connection with the experience we have had with the operation of a rectifier on the Chicago, North Shore, and Milwaukee Railroad. The rectifier is rated at 1000 kw., 600 volts direct current and it is located on the section of the road as shown in Fig. 1. This section is fed also by synchronous converters of 1000-kw. and 1500-kw. rating as shown. This rectifier, made by the General Electric Company, is the first 600-volt machine made in this country which has been installed in actual service.

1. Chicago, North Shore, and Milwaukee Railroad Co., Highwood, Ill.

Presented at the Regional Meeting of District No. 5 of the A. I. E. E., Chicago, Ill., November 28-30, 1927.

Efficiency

The efficiency of the rectifier was compared with that of five converter stations by taking measurements on each substation for five months. The results of the records are shown in the accompanying Table I. The efficiency is taken as the d-c. output divided by the a-c. input. The figures include the efficiency of power transformer and converter or rectifier. They do not

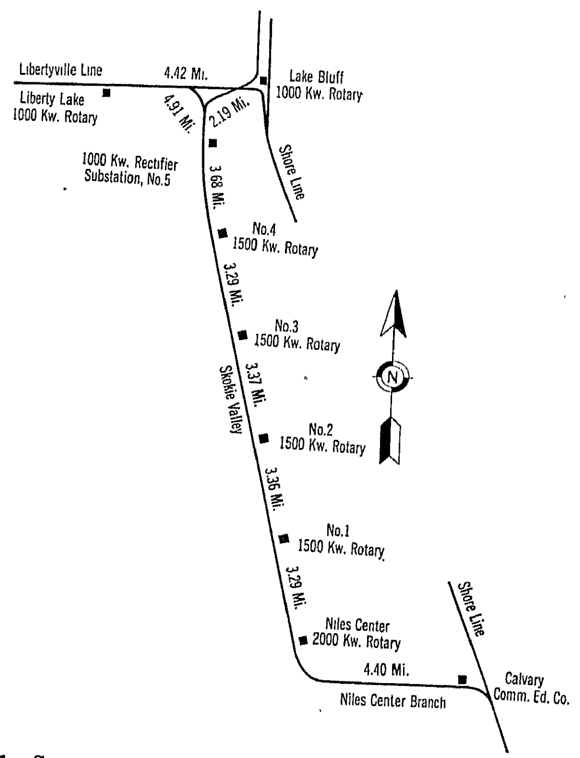


FIG. 1—SECTION OF RAILROAD FED BY RECTIFIER SUBSTATION

Location of synchronous converter substations also shown. Part of Chicago, North Shore & Milwaukee Railroad

include the power used for the operation of automatic devices and auxiliaries such as vacuum pump, motor-generator set, heaters in the rectifier station, nor the power used by auxiliaries and a-c. contactors in the converter stations.

I believe this comparison is fair. It was the best method I had of making a comparison in the short time available for preparing this paper. Although not exactly correct, it shows a pronounced difference in the effi-

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TABLE I

PERFORMANCE OF RECTIFIER AND SYNCHRONOUS CONVERTER SUBSTATIONS

The kw. and efficiency values do not include the power used for the operation of automatic devices and auxiliaries such as vacuum pump, water pump, motor-generator set, and heaters in the rectifier station nor the power used for auxiliaries and a-c. contactors in the converter stations

Substations		Month of May 1927					Month of June 1927					Month of July 1927				
		Total kw-hr.	Total hr. run	Average hr. per day	Average kw-hr. per hour	Per cent efficiency	Total kw-hr.	Total hr. run	Average hr. per day	Average kw-hr. per hour	Per cent efficiency	Total kw-hr.	Total hr. run	Average hr. per day	Average kw-hr. per hour	Per cent efficiency
No. 1. substation.........	A-C. input	87300					86800					82200				
1500-kw. syn. converter...	D-C. output	62130	341	11	182	71.2	59024	300	10	130	68	57140	341	11	167	69.5
No. 2. substation.........	A-C.	43500					34200					34200				
1500-kw. syn. converter...	D-C.	30550	201	6.5	151	70.2	23214	180	6	128	67.8	25294	201	6.5	125	73.7
No. 3. substation	A-C.	69600					74400					78300				
1500-kw. syn. converter...	D-C.	53200	310	10	171	76.5	58200	330	11	176	78.3	60800	341	11	178	77.6
No. 4. substation.........	A-C.	125700					84300					95700				
1500-kw. syn. converter...	D-C.	97900	434	14	225	78	62400	315	10.5	197	74	73000	372	12	196	76.3
Liberty Lake............	A-C.	115950					139950					146100				
1000-kw. syn. converter...	D-C.	83154	496	16	167	71.8	105844	660	22	160	75.6	104263	715	23	131	71.3
No. 5. substation.........	A-C.	89700					75900					79950				
1000-kw. mercury arc rectifier..................	D-C.	71952	403	13	178	80	62857	270	9	232	82.8	65747	387.5	12.5	170	82.2

TABLE I—CONT.

PERFORMANCE OF RECTIFIER AND SYNCHRONOUS CONVERTER SUBSTATIONS

The kw. and efficiency values do not include the power used for the operation of automatic devices and auxiliaries such as vacuum pump, water pump, motor-generator set, and heaters in the rectifier station nor the power used for auxiliaries and a-c. contactors in the converter stations

Substations		Month of August 1927					Month of Sept. 1927							
		Total kw-hr.	Total hr. run	Average hr. per day	Average kw-hr. per hour	Per cent efficiency	Total kw-hr.	Total hr. run	Average hr. per day	Average kw-hr. per hour	Per cent efficiency	Average effic. of each substation, per cent	Average kw-hr. per hour	Grand average effic., per cent
No. 1 substation......................	A-C. input	95700					84300							
1500-kw. syn. converter...............	D-C. output	69770	403	13	173	72.9	61190	330	11	185	72.6	70.8	167.4	73.4
No. 2 substation......................	A-C.	32100					50220							
1500-kw. syn. converter...............	D-C.	21133	186	6	113	65.8	33197	240	8	138	66.1	68.7	131	
No. 3 substation......................	A-C.	104400					95370							
1500-kw. syn. converter...............	D-C.	83200	372	12	223	79.7	75300	360	12	209	78.9	78.2	191.5	
No. 4 substation......................	A-C.	84600					83040							
1500-kw. syn. converter...............	D-C.	65800	310	10	212	77.8	62300	285	9.5	218	75.	76.3	209.2	
Liberty Lake..........................	A-C.	119250					118740							
1000-kw. syn. converter...............	D-C.	88246	434	14	203	73.1	88731	525	17.5	169	74.7	73.3	166	
No. 5 substation......................	A-C.	70215					83460							
1000-kw. mercury arc. rectifier.	D-C	56721	341	11	166	80.7	67868	420	14	161	81.3	81.7	181.4	81.7

ciencies of the two types of equipment under nearly similar load conditions and very low load factor.

Very High Capacity to Absorb Momentary Overload

The ability of the rectifier to carry high momentary overloads is seen from the accompanying Fig. 2 which shows a graphic ammeter chart.

This chart was taken 12 hr. after the unit was put in operation on a day of extremely heavy traffic. It shows load peaks much above the rating of the rectifier. There were no signs of being overloaded, an occasional opening of the high-speed circuit breaker which would reclose immediately, was the only trouble experienced in carrying this load.

Fig. 3 shows the typical load on the station. There are many very high load demands of short duration, some of them well above the rated capacity of the rectifier.

On sustained overload we are not in position to give much information. Usually the load demand above the rectifier rating is of short duration, but there are unusual conditions on the railroad when a load of 175 or 185 per cent of the substation capacity may be

carried by any of these stations. The duration of this load is controlled by thermostats on the load-limiting resistors set to release this load in about six or seven min.

It is, however, possible to have a load above the rating of the equipment and below the 175 per cent overload relay setting for a much longer time than 7 min. A load of this kind would be without thermostatic control and might last indefinitely. It could be caused by traffic schedule disarrangement on account of trouble, extra passenger or freight service, or a trolley wire on the ground at such a distance that the resistance of the feeders would limit the current.

Happenings of this nature are not unusual on a railroad and I believe that we have more than one time imposed on the rectifier an overload of much longer duration than we know. There are no recording instruments to show when this occurs. The rectifier does not show any signs of having been abused; momentary opening of the high-speed circuit breakers is the only indication that there must have been excessive load.

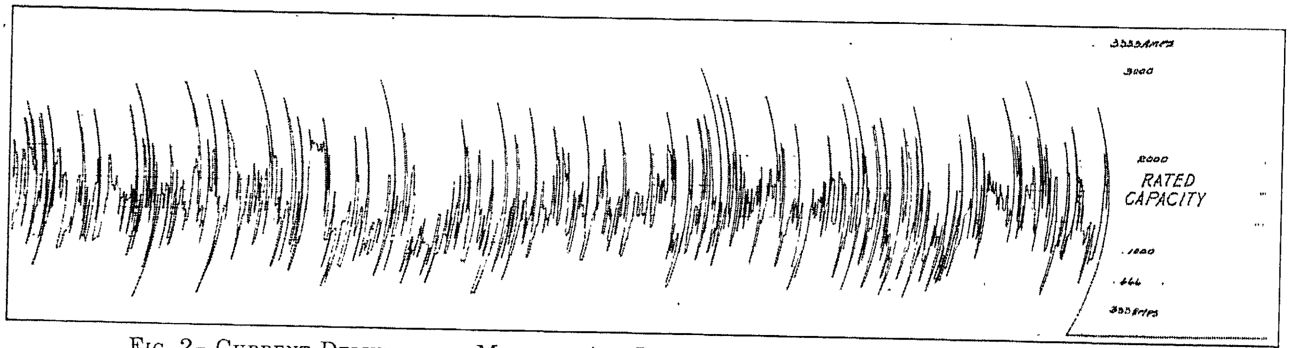


FIG. 2—CURRENT DELIVERED BY MERCURY ARC RECTIFIER ON DAY OF EXTREMELY HEAVY LOAD

Part of record of June 24, 1926 on Substation No. 5 of Chicago, North Shore, and Milwaukee Railroad

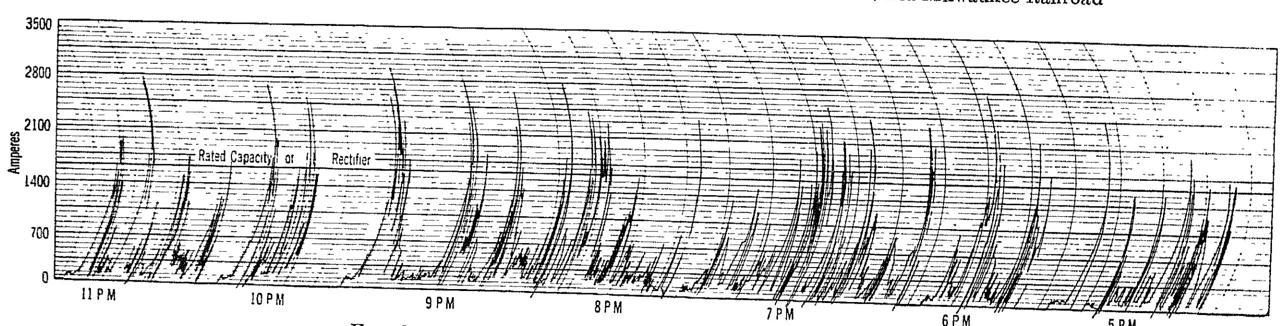


FIG. 3—TYPICAL LOAD ON THE RECTIFIER SUBSTATION

FIG. 4—1000-KW. MERCURY ARC RECTIFIER AND AUTOMATIC SWITCHBOARD

Substation of Chicago, North Shore, & Milwaukee Railroad

INSENSITIVITY TO SHORT CIRCUITS

Our experience shows that the rectifier is not sensitive to short circuit. Repeated reclosing on a short circuit does not affect the rectifier. Under the same treatment a synchronous converter of the same capacity would be likely to flashover regardless of the protective devices, and in an automatic substation it would lock itself out and the station would be shut down until an inspector could put it back in service.

NO SYNCHRONIZING

The fact that synchronizing is not necessary with the rectifier is quite important. In the automatic stations on our system only 4 to 6 sec. are required to connect a rectifier to the line. From 20 to 35 sec. are required to put a converter on the line. Therefore we can deliver a higher voltage to the train and trolley 16 to 29 sec. sooner with a rectifier.

SIMPLE OPERATION AND MINIMUM ATTENTION

We must agree that the mercury arc rectifier requires less attention than the synchronous converter, and its operation is much simpler. There are no brushes, commutator, nor slip-rings to take care of. There is no dust spreading over the equipment. These advantages are very much appreciated in automatic stations without attendance. The ventilation of the equipment and

building is also simplified as compared with converters, especially in unattended stations.

I do not want to create the impression that there are less devices involved in the mercury arc rectifier than there are in the converter station. On the contrary, with the rectifier more auxiliaries are used, such as arc-starting exciters, vacuum pump, water supply, temperature regulators, tank heaters, etc. While in our case some of these devices have caused a large number of shut-downs, the troubles were in the individual pieces of apparatus and they have been corrected. Those devices should not need much attention.

Noiseless Operation and No Vibration

The absence of vibration and noise in the mercury arc equipment makes it possible to install it in locations where the synchronous converter would not be allowed. In one converter installation it cost about $8000 for sound-proofing and ventilating the substation building, eliminating the noise to comply with the wishes of the surrounding residents. Such expense would not have been necessary with mercury arc equipment. Incidentally in addition to the first cost we have added ventilating equipment and extra building maintenance. Obviously, with the absence of vibration it is not necessary to install special foundations for the rectifier. It may be set on an ordinary floor. Ventilation becomes of minor or no importance, and in general a less expensive building is required.

Lower Maintenance Cost

We do not know at this time just what maintenance will be necessary on the rectifier.

From May 1926 to May 1927 this station was attended by an operator and the manufacturers of the rectifier kept a close watch on its performance. Being in a development or trial stage they took care of necessary maintenance. In addition, new developments which they made in other installations were applicable to this equipment and minor changes were made accordingly. Since May of this year this equipment has been in automatic operation without an operator. The maintenance required is very little; outside of the regular weekly inspections it has amounted only to applying a little oil. Like others we are watching this item with a great deal of interest. Our impression is that the maintenance will be very much less than that required for a converter although some manufacturers may have stretched this point a little too much. Time will tell.

Reliability of Service

The automatic rectifier station is as reliable, or more reliable, than the average 60-cycle synchronous converter station of the same capacity.

The record for this rectifier substation, commencing May 1926, when it was first started and put in service, all through a trial and adjusting stage until May 1927, when it was made automatic is as follows:

RECORD OF SHUT-DOWNS OF RECTIFIER

Cause of shut-down	No.	Total time, min.
High temperature of tanks	2	48
Exciter trouble	39	536
Driving chain and motor on water pump	13	315
Loose connection and bad control circuit	3	50
Vacuum-pump trouble, motor and oil pump	3	260
Flashover of anodes	6	819
Starting anodes sticking	5	602
Misc. unknown	12	1109
Total shut-downs	83	3739

Total time rectifier operated 337,140 min.

Shut-down by failure of	No. of times	Ave. time min.	Per cent of time of operation
Rectifier	25	58	0.435
Auxiliaries	58	39	0.674
All	83	45	1.109

Commenting on the foregoing data, it is of interest to note that the time the rectifier was out of service on account of troubles with the rectifier itself was 0.435 per cent of the total time. The time lost on account of the auxiliaries failures was 0.674 per cent of the total time.

The nature of the trouble with the auxiliaries is rather interesting. A larger amount of trouble might be expected with the rectifier on account of its newness in the field, but to have a small motor-generator set or a chain on a water pump and motor cause this bad record is out of place in our days. Engineers have been building and operating motor-generator sets and water pumps for years, but in this case we were after the big things but let the little things cause the most trouble. Fundamentally the record is good, the nature of the troubles is not serious. Since May 1927 the record as an automatic substation is as follows:

Failure in auxiliary	No. of shut-downs
Motor on one vacuum-pump burned out	1
Locked out after third reclosing of the oil circuit breaker within a definite time during storms	3
Locked out on account of broken spring on oil-switch mechanical latch	3
Locked out after third reclosing of the oil circuit breaker within a definite time, cause unknown	5
Fuse blown on operating transformer supplying power for the operation of devices	1
Total shut downs	13

Of all these shut-downs, the five lock-outs after the third closure of the oil switch could be questioned and possibly may have been caused by arc-back in the rectifier, or other troubles in the control which we have not detected. All the remaining troubles were not inherent with the rectifier, but were caused by other devices.

Our confidence in its reliability is such that we have

established a weekly inspection for this rectifier station, but we do not consider it advisable at present to leave a converter so long without inspection.

The record of the rectifier was compared with that of a synchronous converter of modern design and of the same capacity. This converter is located on another section of the railroad where the load conditions are about the same. It is protected from excessive loads by load-limiting resistors without high-speed circuit breakers. In this comparison I used none of the converters shown in Fig. 1 because these converters are of larger capacity than the rectifier and naturally they are more stable and would take a larger shock and carry more load without flashing over; nor have I used the converter at Liberty Lake, Fig. 1, as the momentary load demands on this station are less than they are on the rectifier.

The converter which I compared had 45,434 hr. of run on its record on May 1927 and had 34 flashovers causing as many shut-downs, representing 276 hr. out of service on account of flashovers. There was an average of 8.1 hr. out of service per shut-down as the majority of these flashovers, damaged commutator flash barriers, brushes, brush rigging, and the insulation in other parts of the machine.

Since May 1927 to date this same converter flashed over 8 times and due to the many flashovers which this machine has had, extensive repairs had to be made on the commutator, rings, and other insulation involving 150 hr. in one shut-down.

This record seems to indicate that the troubles with the rectifier itself probably will not be as serious as with the converter of the same capacity under similar load condition.

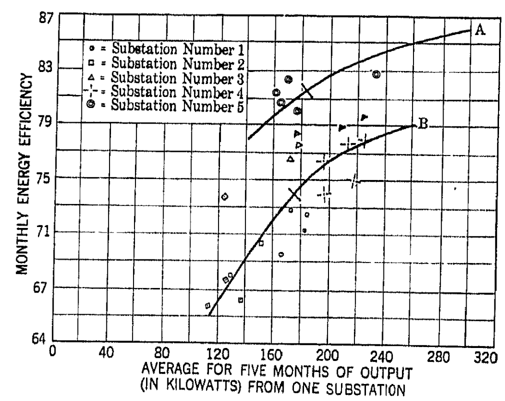
The writer has great confidence that the mercury arc rectifier is here to stay and predicts that 10 or 15 yrs. from now a large application supplementing the converter. The converter had its day, the rectifier's day is coming. It is true that the rectifier at present costs more than the converter of the same capacity and there is some misunderstanding as to its rating. But with an increasing number of installations and our co-operation, as operators, with the manufacturers, the development process will be speeded up and the production cost will naturally be reduced to a figure comparable with that of the converter.

Discussion

H. M. Hobart: (communicated after adjournment) It is sometimes said that there is little or no justification for employing the mercury arc rectifier for systems with as low a pressure as 600 volts. While the superiority of the rectifier may, speaking generally, be said to increase with the voltage of the system supplied, Mr. Antoniono's investigations show that it has a notable economic advantage over the synchronous converter even at 600 volts for the kind of service for which it is employed on the Chicago, North Shore, and Milwaukee Railroad.

Analyzing the data given by Mr. Antoniono in Table I, we find that for the five months covered by the records the 1000-kw., 600-volt rectifier substation carried an average load of 181 kw. which is 18.1 per cent of its rated output. For the same period the four 1500-kw. synchronous converters in substations numbered 1, 2, 3, and 4, carried an average load of only 175 kw. which is only 12 per cent of their rated output. (The Liberty Lake 1000-kw. synchronous converter carried an average load of 166 kw. or 16.6 per cent of its rated output, but the author states that on that station the momentary load demands are less than they are on the rectifier substation.) The accompanying illustration contains two curves, A and B, relating respectively to the observed monthly energy efficiencies of the 1000-kw. rectifier substation and the four 1500-kw. synchronous-converter substations of which the data are given by Mr. Antoniono in Table I. At the rectifier's five months average load of 181 kw. the monthly energy efficiency is seen to be 81.5 per cent as against the synchronous converter's monthly energy efficiency, at the five months average load of 175 kw., of 74 per cent.

Thus the rectifier substation has under these conditions 7.5 per cent higher efficiency than the synchronous-converter substations. Furthermore the 1000-kw. rectifier substation during these five months carried substantially as great an average load



(in fact a slightly greater average load) than the average of the four 1500-kw. synchronous-converter substations and it would appear that its cost should be compared *not* with that of a 1000-kw. synchronous-converter substation but with that of a 1500-kw. synchronous-converter substation. However, the sub-stations may have been equipped in anticipation of increasing load and in that case no rigorous conclusions should be drawn.

A study of Curves A and B, leads one to consider whether such substations could not be designed for higher loads than averages of only, respectively, 18 per cent and 12 per cent of their continuous rating. Considering first the synchronous-converter substation it must be remembered that engineers have had many years of experience in applying them to all sorts of loads. It is necessary to install synchronous converters of sufficient size to ensure that the momentary peak-load demands are well below values liable to occasion flashovers. The graphic chart shown by Mr. Antoniono in Fig. 3 of his paper shows the frequent recurrence of momentary peak loads of 1800 kw. and the installation of synchronous converters with a continuous rating of 1500 kw. may not have been unduly conservative even though it entailed the undesirable feature of an average load of only 12 per cent of the continuous rating, and the correspondingly low monthly energy efficiency. The occasionally occurring days of exceptionally heavy traffic when the graphic chart of Fig. 2 applies, do not enter much into consideration in the case of the synchronous converter since with this kind of service it is principally the frequency of the peaks of load, and not to much extent their magnitude which is increased on days of heavy traffic. We have so little experience with the application of mercury arc rectifiers to this kind of load, that we ought to

continue to be conservative in our installations till we have accumulated on several different installations many more data of the kind contained in Mr. Antoniono's paper.

From our present understanding of the rectifier it would appear that the limiting condition will not be with momentary peak loads as in the case of the synchronous converter, but in sustained heavy loads. Consequently *not* the momentary peak loads but sustained heavy loads on the occasional days of heavy traffic are, in the case of rectifiers, liable to constitute the limiting condition which will determine for this kind of service to what extent we can properly increase the percentage which the average load may constitute of the continuous rating. It may be that while the synchronous converter has such limitations for this kind of service that the monthly average load should be limited to a matter of not much over 12 per cent of its continuous rating, the rectifier substation may not need to be so limited. Indeed it is emphasized at several places in Mr. Antoniono's paper that the rectifier substation, for the conditions under which it is operating, is giving a better account of itself than the synchronous-converter substations at the conditions under which they are operating. If further experience bears out this impression, then the efficiency of the rectifier substation may be moved further up on Curve *A* than the efficiency of the synchronous-converter substation can be moved up on Curve *B*.

It thus appears reasonable to assess at some 7 or 8 per cent the amount by which the rectifier substation's efficiency will be higher for a 600-volt load of this character and to compare the initial costs on the correspondingly revised basis. Mr. Antoniono's comments on this conclusion would be much appreciated.

The efficiencies obtained by Mr. Antoniono and set forth in Table I of his paper are, both as regards the synchronous converter and the mercury arc rectifier, several per cent lower for the average loads to which they correspond than the efficiencies which would be obtained for constant loads of these same values. For instance, the efficiency of the 600-volt rectifier and transformer at 18 per cent of rated load should be about 87 per cent while in Table I the efficiency at this load is given as 81.7 per cent. This is partly due to the load characteristics shown in Fig. 3. For the periods when the load is *below* the average, the efficiency is lowered much more than it is raised by load values *above* the average. Will Mr. Antoniono state if he agrees that this is the explanation of the discrepancy? Furthermore, did not the 1000 kw. of equipment in substation No. 5 consist of two 500-kw. rectifiers?

In conclusion it may be of interest to point out that the improvement in the efficiency which is obtained in the case of the rectifier substation when it supplies a greater load is due exclusively to the improvement in the transformer's efficiency, the efficiency of the rectifier itself being nearly constant at all loads. But in the case of the synchronous-converter substations the efficiencies of transformer and converter both improve with increasing load.

W. B. Anderson: (communicated after adjournment) Mr. Antoniono's paper includes operating and performance data of value to the many engineers who are carefully observing the development and application of the metal-tank mercury arc rectifier in this country. The comparative performance data for four rotary-converter stations and the one rectifier station tabulated under Table I are particularly interesting. The comparative values of over-all efficiency clearly indicate the decided advantage of the rectifier over the rotary converter for applications where the average load is small.

In connection with the various advantages of the rectifier, it might be well to consider some of them in further detail. Building-construction costs for rectifier substations should be substantially less than for substations built to house rotating apparatus. As Mr. Antoniono mentions, converter-substation building costs may include items for special ventilation or noise elimination. The matter of foundation, crane, and wall-construction costs should be of considerable importance. A 1000-kw. 600-volt rotary converter weighs approximately 20,000 lb., its heaviest part weighing between 12,000 and 14,000 lb. A rectifier of equivalent capacity will weigh approximately 5000 lb., the heaviest part weighing about half that amount. The foundation for the converter must not only carry four times the weight, but must be adequate to withstand the vibrations of rotating equipment. In most cases, the rectifier will require no special foundation at all. It is common practise to install a crane in the substation suitable for lifting at least the heaviest part of a machine. The rectifier has the advantage in this instance of almost five to one and for the average rectifier installation no crane should be necessary. In addition, wherever there can be a saving in crane service, there will be a corresponding economy in the cost of substation wall construction. The ultimate result should be a considerable saving in building costs for the lighter and static piece of apparatus. The engineers of one railway property have estimated that approximately $5000 can be saved on a $20,000 substation building by the use of rectifiers rather than rotary converters.

The fact that a given rectifier is suitable for operation at any commercial frequency without a change in rating is another interesting feature. This characteristic of the rectifier may result in its preference to the exclusion of rotating apparatus for certain applications. For instance, let us consider the following example. A given property needs more substation capacity immediately and has only 25-cycle power available. Within a space of two years, the 25-cycle power will be replaced by 60-cycle power. At a small added cost, the transformers can be made good for 25 or 60 cycles and the rectifier itself will need no changes. As another possible application, let us consider a property which is supplied from an a-c. system of an odd frequency. Rotary converters of standard frequency would prove unsatisfactory so that it would be necessary to use de-rated motor-generator sets of standard frequency. By using rectifiers no sacrifice in rating is necessary.

The rectifier has another advantage as regards its applications at different voltages. The fundamental basis of rating for a rectifier is current. Representative curves of the voltage rating at different current ratings have already been published. For instance a given design of rectifier with a rating of 1000 kw. at 600 volts will have a higher kw. rating at 1500 volts. A rectifier could be advantageously applied to a 600-volt system which might later be operated at 1500 volts by a change in transformer connections.

Mr. Antoniono refers to the use of a larger number of auxiliaries on a rectifier than on a rotary converter. I believe that a careful check of the major auxiliaries used on a representative installation of each class of equipment, will show the number to be very nearly the same. In this connection a comparison of the number of control devices required for a typical synchronous-converter station and rectifier station respectively might be interesting. In the October issue of the *Electric Journal*, Mr. M. E. Reagan gives the following comparison:

	No. of Major Switching Devices	No. of Relays Functioning	No. of Protective Relays
Converter.....	14	11	13
Rectifier.......	9	10	10

However, any comparison made now as to the relative number of auxiliaries and control devices used for each apparatus may be misleading. The rotary converter is a highly developed piece of apparatus while the rectifier is in its infancy. The next few years will see many changes in the rectifier, its auxiliaries, and its automatic control equipment.

F. D. Newbury: I think the thing we need most to increase the application of rectifiers is a study of the fundamentals involved in rectifier operation. I think I am correct in

saying that all rectifiers, as they are built today by anybody, are built purely on empirical information and rules. We know relatively little of the fundamentals on which the rectifier works.

There is no such limit to rating as there is in the converter or any other electromagnetic machine as in flux and current densities. The amount of current a rectifier will give depends largely on local temperatures and characteristics of materials, and ability to exclude gases from the rectifier tank. A study of those fundamentals will undoubtedly lead to very great reductions in the size of rectifiers for a given current rating.

I don't agree entirely that the case chosen is a fair example from the standpoint of the converter, and remember in what I am saying now all of the nice things I have just said about the rectifier.

It is obviously unfair to compare efficiencies on the basis of stations having such low load factors. It is possible, particularly with automatic stations, to have fairly high load factors, and with high load factors above 50 or 60 per cent of rating there will be no such outstanding difference in efficiency in favor of the rectifier as shown in this case.

Again, in the comparison of short circuits, there is any number of large 60-cycle converters that are operating under severe conditions with practically no flashovers. Probably the greatest need for the rapid application of rectifiers is the ability of manufacturers to supply larger units. That is particularly true at 600 volts. Much of the advantage of the rectifier in station cost is lost if a large number of tanks has to be supplied to give the desired unit rating.

M. S. Oldacre: There are two characteristics of the rectifier that have not been emphasized that make the rectifier desirable for other applications than these now usual in this country, and these are the absence of noise and ease of cooling.

In the congested districts of the large cities where rotary converters are used for supplying 250-volt distribution systems, the question of noise and cooling is a problem at the present time. The rectifier solves the noise problem at once. The cooling question is practically solved because the amount of water required is a small fraction of that required by a converter installation, where recirculation of the air is required to obtain adequate cooling if space is restricted. The rectifier gives a much simpler layout.

The rectifiers discussed have a capacity in a single bowl of only 500 to 1200 kw. at 600 volts, and it has been pointed out that large enough rectifiers for 250-volt service are not yet available, the requirements being about 15,000 amperes; but with rectifiers available having a nominal rating of 5000 amperes and a two-hour rating of 7500 amperes at 600 volts and in a single bowl, the indications are that the larger rectifiers may soon be available.

Another point is that apparently the rectifier has been developed in this country and its characteristics are well known to the manufacturers or at least well enough so that they are able to build them after the rectifier has been popularized by some other manufacturer, in this case a foreign manufacturer. It does not seem up to the usual pioneer spirit of our American manufacturer to trail along in that fashion.

Sidney Withington: (communicated after adjournment) It is quite refreshing to read a paper on the mercury arc rectifier which is written by a user rather than by a manufacturer of this type of apparatus. The enthusiasm of Mr. Antoniono for the rectifier is apparent, and is obviously justified by the performance.

The Connecticut Company a few months ago placed in operation a 6000-kw. substation at Bridgeport, Conn. (the largest installation of mercury arc rectifiers thus far made, and the only instance where an entire city traction load is carried by this type of apparatus), consisting of five single-bowl rectifiers rated at 1200 kw. each. From the impressive manner in which the substation went into service, with little or no time available for test before it was called upon to carry the load commercially, and from subsequent operation, it is obvious that the mercury arc rectifier is here to stay as an integral facility for traction purposes, and that it has numerous and important advantages over the rotary converter.

The rapid development of this type of apparatus places upon electrical engineers, both manufacturers and users, responsibility for standardization, especially of rating, which cannot be ignored. The load characteristics of the rectifier are so different from those of the rotary converter that attempts to rate one in terms of the other are misleading, and it is imperative that the rating of the rectifier be placed upon a sound and logical basis as soon as possible.

B. G. Jamieson: I should like to say that Mr. Schuchardt, Electrical Engineer of the Commonwealth Edison Company, went abroad some six or seven years ago and came back and tried his utmost to get the American manufacturers to interest themselves in this problem, and it is very largely due to his efforts that we now have the rectifier in actual operating performance.

There are one or two other points in connection with the rectifier, one suggested particularly by the lack of necessity of synchronizing. As the rectifier becomes a feature of future trunk-line electrification, we shall see the advantage where the supply of energy has to be taken from different systems. We shall not be bothered with energy interchange between the different systems through trolleys.

There are some other points about the rectifier not so favorable at present. For example, there has not been, so far as I know, any substantial accomplishment toward improvement of regulation. When the requirements of the railway companies take the form of very close regulation and a rectifier is involved, it becomes necessary to look beyond the present art.

Another unfavorable feature of design which unnecessarily exaggerates rectifier outage and which should be corrected is, for example, a case of trouble with an anode, the mechanical replacement of which should not take an hour, but which because of incidental circumstances causes the rectifier to be out of service for 100 hr. Certainly any over-all figure which Mr. Antoniono has given has some elements of this character which exaggerate the reported unfavorable performance.

Other features of the rectifier which were regarded some years ago as basic difficulties have been minimized, but there are still some such features as for example, the question of unknown characteristics of the backfire and the reasons therefor.

A. Herz: The matter of noise emitted from rotary converter substations is serious. As the railroad load increases the substations must be located closer together making it unavoidable to locate some in comparatively densely populated sections which in many instances are the better class of residential suburbs.

In our company we have carried on experiments to mitigate the noise by closing window openings with two thicknesses of glass and lining the substation doors and walls with non-sound-transmitting and non-reflecting materials, with the result that artificial ventilation with its noisy blowers, etc., had to be resorted to if temperatures of 110 to 125 deg. fahr. in the summer time and inside the converter substations were to be avoided.

Therefore if we can use a rectifier which is inherently noiseless in place of a converter and do the necessary cooling for the former outside of the substation we have certainly made an advance in every way.

This brings up the matter of cooling the rectifiers. We have had serious trouble with the cooling systems of rectifiers, cases of electrolysis and cases of deposition of mineral matter, the former being particularly serious.

I cannot quite comprehend why the manufacturers do not resort to oil as the initial heat-absorbing medium; that is, use oil for cooling the rectifier proper and circulate this oil through a cooling system making use of fans or water. This would avoid troubles from electrolysis within the rectifier as is now the case

and would avoid some other difficulties we now have. The quantity of oil necessary would be quite small.

There is one feature that has not been touched upon, I believe, and that is the item of stored energy. A power system with many large rotary converters in operation thereon has certainly considerable energy stored in the momentum of the moving parts of such machines. The stored energy in the rectifier is practically nil. Therefore an accident occurring to the power system is not aggravated nearly as badly by a rectifier load as by a rotary-converter load.

The item of back-fire has already been mentioned by Mr. Jamieson, and I believe improvements are being made in the rectifier to do away with it, but in any event the back-fire in a rectifier is not more serious than a flashover on a rotary converter which I know we still get although not so frequently as during the times before barriers and arc hurdles were installed over the commutators.

O. K. Marti: This paper, written by an operating engineer who has had actual experience with equipment of this kind, is a very good contribution to the rectifier art in this country. It is highly desirable that more operating and service data be made available, because the mercury arc rectifier is a device only recently introduced into this country, and although the rectifier is used to a very great extent in Europe, where there are installed more than 1500 cylinders with a total capacity of about 700,000 kw., there are very few operating data available.

I feel that Mr. Antoniono's paper permits a comparison between the performances of rectifiers and rotary converters in a number of points, such as efficiency, overloads, service interruptions, and the like. There is one point, however, on which it is very hard to come to an impartial conclusion, and that is in the matter of interruptions caused by back-fires (in the case of rectifiers) and by flashovers (in the case of rotary converters). Flashovers produce damage to brushes, brush-holders, commutators, and armatures, and very frequently put the machine in such a condition that it cannot render any service for several days. Back-fires, on the other hand, do not cause an interruption of service for more than a few seconds. In making this comparison one has to keep in mind that in an automatic rectifier substation there is less auxiliary equipment than in an automatic rotary converter substation, and that a rectifier is stationary, while a synchronous converter is rotating. This is another fundamental difference which complicates the problem of making a comparison.

I should like to point out particularly some points relating to the table on the fourth page of Mr. Antoniono's paper, which gives a record of the shut-downs of the rectifier in question. You will notice that most of these shut-downs were due to the auxiliaries, and not to the rectifier proper, as might be expected, and this peculiarity is also pointed out in the paper. It can also be seen that the largest single item, 39 interruptions, was due to exciter troubles, and 5 interruptions were due to the starting anode which is used to ignite and put the rectifier into operation. I should be pleased to have Mr. Antoniono tell us the failure of what particular part of the exciter caused these troubles.

In the installation described in this paper, the arc is ignited by direct current supplied by a small motor-generator set. A starting anode is used which, when withdrawn from the mercury cathode, strikes an arc. This interruption of the current frequently induces a high voltage in the starting circuit, which may cause a break-down of the insulation in the generator or a flashover at its commutator. Brown Boveri employed a similar system of ignition and excitation and experienced similar troubles but as the result of extensive investigations they were able to devise an arrangement for using alternating current for these purposes. Although similar voltage surges occur in the a-c. system, it is much easier to insulate a transformer for these surges than a d-c. generator, and no troubles are experienced with the ignition and excitation system now in use. Furthermore, the Brown Boveri rectifiers do not have any anode heaters nor tank heaters.

It might also be interesting to note that the limits in the capacity of power rectifiers, which were at about 1000 kw. at 600 volts, nominal rating, have now been raised, the American Brown Boveri company offering rectifiers for 6000 kw. at 600 volts, nominal rating, at the present time. This shows that rectifiers can be built for capacities as large as and larger than rotary converters. Furthermore, there are no difficulties with rectifiers in connection with the frequency or the voltage. This is an achievement of great importance. It is therefore likely that Mr. Antoniono's prediction that in 10 or 15 years the rectifier will take the place of the rotary converter, will come true even sooner.

This increase in capacity was made possible by a recently made improvement, the basic idea of which dates back several years. Tests carried out on the latest types of large rectifiers for several months at loads greatly in excess of their capacity ratings have demonstrated their reliability, and therefore the future outlook for the mercury arc rectifier is an excellent one.

Caesar Antoniono: The conclusion reached by Mr. H. M. Hobart on my paper is in general in accord with my own conclusion.

The size of the substations units shown in Fig. 1 was decided on in anticipation of future increase in load. The rectifier however, was the largest that could be obtained at that time. While it is true that the load is carried by each converter in its respective section, it is also expected to be carried by the rectifier through its own section as shown in Fig. 1. I agree with Mr. Hobart that we should not arrive at any rigorous conclusion on this point at present regarding cost and rating.

I do not consider that the installation of 1500-kw. units in these substations was unduly conservative, due to the fact that all of the synchronous converters shown in Fig. 1 have already flashed over, due to some disturbance or other which has passed by the high-speed circuit breakers into the d-c. feeders.

I agree with Mr. Hobart's deduction, that sustained overloads are perhaps the limiting conditions on the rectifier, and not the value of the momentary loads. I believe we should have further experience on this subject to support or disprove this conclusion.

I believe it in order at this time to call attention to my discussion on the mercury arc rectifier at Kansas City, March 18, 1927,[1] in which reference is made to a case where one tank of the rectifier under discussion was not carrying any load for over a week, unknown to the operator. The writer feels justified in assuming that during this time the working tank was carrying alone the (typical) load on graphic chart Fig. 3 without showing any sign of having been over-loaded. The assessment of 7 or 8 per cent of the amount by which the rectifier substation's efficiency will be higher for a 600-volt load of this character and to compare the initial cost on this correspondingly revised basis, seems to be a logical conclusion from the data given in my paper. However, we should be rather conservative at present and obtain more data before arriving at a conclusion, in order to avoid the possibility of leaving out some important factor.

The discrepancy in efficiency as referred to in Mr. Hobart's discussion is correctly quoted in his explanation of the load characteristics shown on Fig. 3. Two 500-kw. tanks of 6-anodes in 12-phase relation are employed.

It was brought out that the number of devices in the future is going to be less. I agree with that, but in my paper I was speaking of present installation. I am confident that the number of automatic devices for the mercury-arc rectifier is eventually going to be reduced to fewer devices than required for the converter.

Mr. Newbury brought out that the method of comparing the two efficiencies was not fair. I stated in my paper that this

1. A. I. E. E. Journal, October 1927, p. 1104.

method was not exactly correct. But from the point of view of the operator we are concerned with the total efficiency we are getting from the two different types of equipment, and that is what we are getting from this chain of stations under the existing conditions. He brought out the point that a converter could be improved as to load factor and therefore the efficiency would be improved. If that is feasible, yes, but in our case it is not feasible because the load demand on one of these machines perhaps goes much above 150 per cent and is of very short duration. It may last one, two, or three minutes, and perhaps about five or ten minutes an hour, and that accounts for the very low efficiency we are getting out of the stations. The operator is interested in the efficiency he is getting out of his equipment under that condition.

Rotary flashover was also mentioned. There are a number of rotaries that don't flash over. We have about 22 rotaries, and they are subject to flashover in spite of all the protective devices used either with or without high-speed breakers. Up to this time the rectifier has done well.

Mr. Withington stated that I am enthusiastic about the rectifier. I am. From the experience we have had so far with the rectifier, I am very enthusiastic about it.

Mr. Jamieson brought out the question of changing the anodes or similar maintenance work, and the number of hours before the rectifier can be put back into operation. That is one thing that as I mentioned in my paper we are not able to tell anything about at this time, and we should like to know ourselves what this is going to be. I feel as Mr. Jamieson does, that improvement can be made or will be made to the extent of eliminating some of the present difficulties with the rectifier and that the future rectifier will be superior to the converter in every detail.

I was informed that one manufacturer is using a carbon anode to eliminate trouble with seals.

With regard to the cooling trouble, it was mentioned by Mr. Herz that there have been cases of electrolysis. I believe there are more or less cases of electrolysis, although we have had no experience with bad effects from electrolysis. I feel as Mr. Herz does, that perhaps there are other methods of cooling. I believe perhaps oil would be the solution of electrolysis.

In connection with auxiliary trouble, I mentioned in my paper that we had trouble in d-c. motor generator sets due to poor operation of the exciters, or commutators, which in turn would result in a shut-down in order to correct it.

Another trouble was with the driving chain and motor on the water pumps. This was due to misjudgment of the amount of water necessary for cooling this particular rectifier. Using a high-speed motor to drive a pump would cause driving chain to jump off and result in a shut-down.

A loose connection in the control circuit is one of the troubles typical of automatic control. Then there was trouble in a motor which was changed from a 3-phase induction motor to a single-phase motor.

Synchronous Motors for Driving Steel Rolling Mills

BY W. T. BERKSHIRE[1]
Associate, A. I. E. E.

and

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Synopsis.—It is the purpose of this paper briefly to discuss, from a practical standpoint, the application and design of synchronous motors for steel-mill main-roll drives, in an effort to show what their advantages and disadvantages are; where they should, and where they should not, be used; and what special precautions must be taken in the design of motors for this service.

DRIVING main rolls of steel mills is universally recognized as very heavy duty. The loads are high, and are applied and relieved very suddenly. Consider the case of a motor driving a single stand, Fig. 1. Between passes it will run with only 5 per cent to 10 per cent load, due simply to mill friction. As the metal strikes the rolls the load jumps almost instantly to possibly 100 per cent or 150 per cent of normal, and is as suddenly reduced when the metal leaves. This happens several times a minute. If such a drive has been properly selected, several passes on each bloom or billet may require 150 per cent to 175 per cent normal load on the motor. The load is intermittent in character, so that the motor is selected with the idea of permitting some of the passes to come up to these limits, so long as the r. m. s. value of the load is within the normal rating of the motor. If the heavier passes are of not more than three or four seconds duration a flywheel may be utilized to reduce the peak loads on the motor and power system.

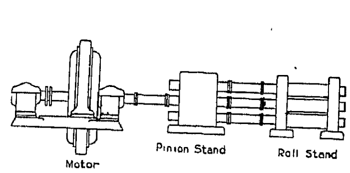

FIG. 1—ROLLING MILL, SINGLE STAND

With a mill having a train of several stands as in Fig. 2 or with a continuous mill as in Fig. 3, the drive is not subjected to quite as severe shocks as with a single stand, for it is apparent that as a piece of metal enters the mill the stands are filled in succession until all are full. The load increases to the maximum value in a number of steps, and is similarly reduced.

The torque required to start a mill from rest is often quite high in comparison to the capacity of the driving motor. This is especially true in cold weather, as very heavy grease is used on the roll necks and pinions, and this becomes very hard at low temperatures. Mills used for cold rolling thin sheets, which operate with very high pressure between the rolls and consequently on the bearings, may require as much as 200 per cent of normal motor torque to break them loose.

In addition to being able to start the mill, and carry heavy and sudden overloads, the drive must usually be capable of withstanding "plugging" in order to bring the mill quickly to a stop in case of a "cobble" or other mishap. Any piece of metal which fails to go through

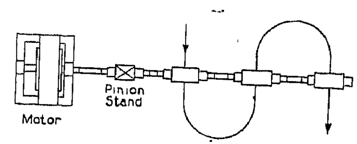

FIG. 2—ROLL TRAIN OF THREE STANDS

the mill properly is termed a "cobble." As soon as the operator sees that the steel is not going through as it should, he "plugs" the motor by disconnecting it from the line and then applying power with reversed phase rotation. After the mill stops, if the metal is not clear of all the stands, the portions between stands are cut out and then the motor must start the mill in the reverse direction to back out the pieces in the rolls.

Considering these conditions which a main roll drive must meet, it is not remarkable that for nearly all constant-speed electric drives induction motors of the wound-rotor type have been used. This type of motor has excellent starting characteristics, will carry heavy overloads, and withstands much abuse. In common with all induction motors, however, its power factor is lagging, and very much so in low-speed machines. Now, the main rolls and lay-shafts on heavy mills do not run at high speeds, and it is often desirable to direct-connect the motor, so that there are now in service many low-speed motors, operating at low power

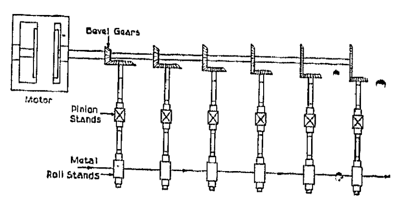

FIG. 3—CONTINUOUS MILL

factors. As a matter of fact, one reason for the use of 25-cycle power in numbers of steel plants is that low-speed 25-cycle motors have better power factor than the corresponding 60-cycle machines. The use of higher speed motors driving through reduction gears

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1. Both of General Electric Co., Schenectady, N. Y.

Presented at the Regional Meeting of District No. 5 of the A. I. E. E., Chicago, Ill., Nov. 28-30, 1927.

pp 636-642 of AIEE. 1928 July June

has helped the situation somewhat, but has still left much to be desired in the way of power factor improvement.

Unquestionably the desire for a better operating power factor has been the chief factor in bringing the synchronous motor into consideration in steel mill service. It possesses, however, advantages other than

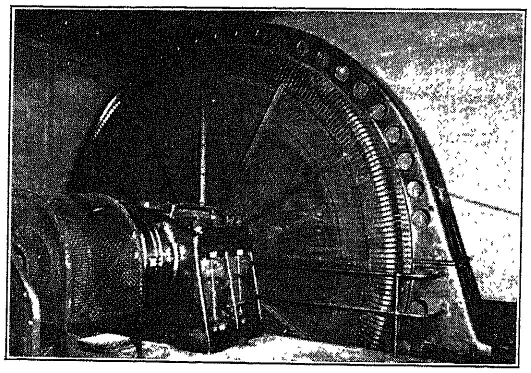

FIG. 4—9000-H.P., 107-REV. PER MIN., 6600-VOLT SYNCHRONOUS MOTOR DRIVING A CONTINUOUS SHEET BAR MILL

This motor has a greater continuous horsepower rating than any other motor in industrial service.

its good power factor, as well as some disadvantages, and these will be brought out in the following detailed comparison of the characteristics of the two types of machines.

FIELD OF APPLICATION OF SYNCHRONOUS MOTOR

The field of application of the synchronous motor in main-roll service is limited to strictly constant-speed drives. This eliminates it from consideration on reversing mills,—mills requiring flywheels, and mills needing adjustable speed.

It is not as a rule advisable to attempt to apply it to any type of mill which may have to be started with metal in the rolls, such as a cold strip mill, nor to cold sheet mills, which have excessively high friction. Such mills may require at starting considerably more torque than is needed to carry their full load at full speed, and unless the motor is sufficiently small in comparison to the power system so that it can be started at full voltage, difficulty may be experienced in getting started and synchronized.

In connection with constant-speed continuous mills of the type shown in Fig. 3, looping mills as illustrated in Fig. 2, and in fact, almost any constant-speed hot metal mill, the synchronous motor deserves very careful consideration. Every individual case must be studied very thoroughly to make certain that no misapplications are made. Careful thought must be given not only to the full-load rating required, but also to the maximum torque that may be necessary to break the mill from rest under the most adverse conditions; to the maximum torque needed at pull-in; to the torque required to back out cobbles; to the maximum peak load that may be encountered; to the kv-a. demand that the power system can stand without disturbance, while starting the motor; and last, but not least, to the characteristics that can be obtained in the motor, to determine whether it can meet the requirements.

STARTING CHARACTERISTICS

Practically the only reason synchronous motors have not been widely used on mill drives in the past is because their starting characteristics are not so desirable as those of the wound-rotor induction motor. For 100 per cent kv-a. input the induction motor develops approximately 100 per cent rated torque at starting, whereas the synchronous motor will give from 30 per cent to 60 per cent starting torque with the same kv-a. input at a much lower power factor. However, the torque obtainable from a synchronous motor is ample to start most types of mills, and its other advantages make it the logical choice in many cases.

By proper design, good starting torque characteristics, as shown in Figs. 5 and 6 can be obtained in mill type synchronous motors with a single squirrel-cage winding. The double squirrel-cage has, at times, been considered, but in each case it has been found that by the proper choice and distribution of materials in the bars and rings, the proper spacing of the bars with respect to the stator slot pitch and the depth and width of the slots in the pole face over the bars, the torque

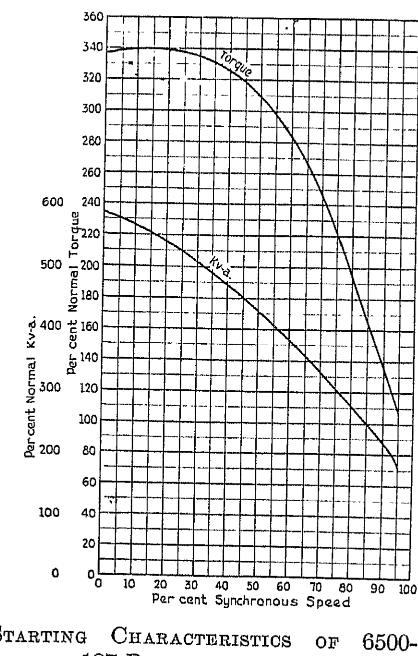

FIG. 5—STARTING CHARACTERISTICS OF 6500-H. P., 0.8-POWER FACTOR, 187-REV. PER MIN., 6600-VOLT, 25-CYCLE SYNCHRONOUS MOTOR, FROM TEST DATA

requirements have been amply met with a single squirrel-cage. In practically all cases it has been found possible to obtain more than sufficient torque to start and bring the mill to synchronous speed, or to even back out a cobble, with from 70 per cent to 100 per cent normal kv-a. input. Unlike that of the squirrel-cage induction motor the squirrel-cage of the synchronous motor can

be changed in design at will, with a corresponding change in torque characteristics, without affecting the efficiency of the synchronous motor during its normal operation under load.

The curves shown give the torque and kv-a. values with full voltage applied to the motor. In normal operation of course, these large motors are started at reduced voltage obtained from a suitable auto-transformer. For example, the 6500-hp., 187-rev. per min. motor for which starting torque and kv-a. curves are

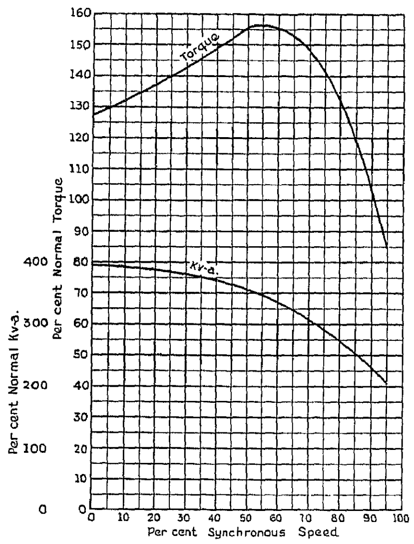

FIG. 6—STARTING CHARACTERISTICS OF 5000-H.P., 0.85-POWER FACTOR, 240-REV. PER MIN., 2200-VOLT, 60-CYCLE SYNCHRONOUS MOTOR, FROM TEST DATA

shown is regularly started on 32 per cent voltage. Since the starting torque and kv-a. input varies as the square of the voltage, it is apparent that under this condition the motor demands only 60 per cent of normal kv-a. and gives about 35 per cent of its normal torque. This has proved ample to start the mill under all conditions. Similarly, a 9000-hp., 107-rev. per min. motor is always started at 32 per cent voltage, giving 27 per cent of normal torque with 70 per cent normal kv-a.

The "pull-in" torque, or the torque available at approximately 95 per cent synchronous speed before the application of field, must of course be in excess of the mill friction at this speed, but can be considerably less than the starting torque, as the latter must overcome the "dead" friction of the mill, with the bearings practically dry.

The fields of these motors are usually wound for 250-volt excitation, and if the field were left open-circuited at starting the induced voltage across the rings, with 33 per cent normal voltage applied to the stator, would be from 5000 to 10,000 volts. In order to protect the operators from the induced field voltage it is the practise when starting, to close the field circuit through a discharge resistance. While this increases the starting current and decreases the starting torque to some degree, it also increases the pull-in torque. The amount and capacity of this resistance to give the best torque characteristics can be determined by calculation.

A synchronous motor may be plugged for a quick stop, by first opening the "forward" breaker and removing field, then closing the "reverse" breaker and connecting the motor to the starting tap of the auto-transformer. The current drawn when plugging is approximately 15 per cent more than the starting current, and the torque developed about 75 per cent of the torque at starting.

MAXIMUM TORQUE

A synchronous motor can be designed for fully as high maximum or pull-out torque as an induction motor and for steel mill service this pull-out torque varies from 225 per cent to 300 per cent of normal full load running torque. The synchronous motor has the advantage that for any reduction in applied line voltage the pull-out torque decreases only in direct ratio to the voltage, whereas the torque of an induction motor decreases as the square of the voltage. Furthermore because of its better power factor, the synchronous motor helps to maintain the voltage at its terminals; consequently the drop in line voltage due to a given load is not likely to be so great as if an induction motor were used.

POWER FACTOR

One of the most desirable features of the synchronous motor is its ability to improve the power factor of the system on which it operates. It is usually designed to give a leading power factor at normal load, and will then

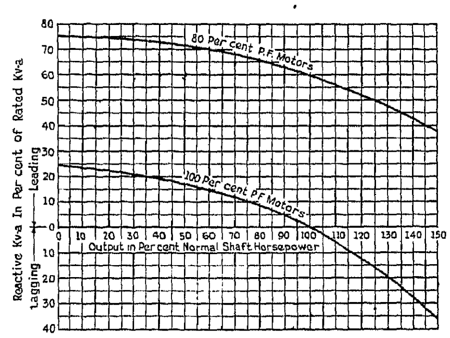

FIG. 7—APPROXIMATE REACTIVE KV-A. AVAILABLE FOR POWER-FACTOR CORRECTION, WITH FIELD EXCITATION CONSTANT AT NORMAL LOAD VALUE

furnish a considerable amount of corrective kv-a. at all loads up to a considerable overload, as shown in Fig. 7. The low power factor of low-speed induction motors, particularly 60-cycle machines, has necessitated the use of reduction gears in some cases where for other reasons a direct drive would have been preferable. The use of synchronous motors permits direct drive with low-speed machines, operating at unity or leading power factor.

Efficiency

Two curves are shown, illustrating the very high efficiency obtained from large synchronous motors, both 25 and 60 cycles. The fact that approximately 75 per cent efficiency is obtained at 5 per cent of normal load is quite noteworthy.

The full-load efficiency of synchronous motors for steel mill service varies from 0.5 per cent to 2 per cent more than that of the corresponding induction motors. This better efficiency of course means some saving in power cost.

Operating Voltage

Synchronous machines can very readily be built for any operating voltage up to and including 13,200. While a very few induction motors are operating at 13,200 volts, it is better practise not to exceed 6600 volts on an induction motor, as the design becomes difficult and the machine expensive.

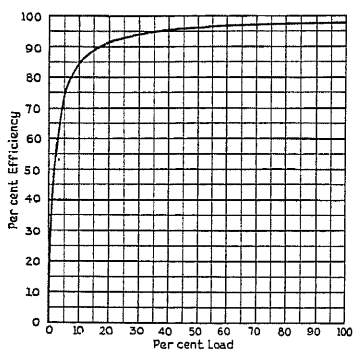

Fig. 8—Efficiency of 9000-HP., 1.0-Power Factor, 107-Rev. Per Min., 6600-Volt, 25-Cycle Synchronous Motor, from Test Data

Excitation

One disadvantage of the synchronous machine is that it requires a separate source of excitation, while the induction motor does not. On an important drive it is wise to employ an individual exciter, either direct connected or driven by a separate motor. The excitation voltage is always 250, so that as an emergency source the 250-volt d-c. power circuit which exists in all steel mills can be used.

Floor Space

The amount of floor space required by a synchronous motor is almost invariably less than that needed for an induction motor of the same rating. One reason for this is that it is the usual practise to make the motor base long enough so that the stator can be moved along the shaft a sufficient distance to make both rotor and stator windings accessible for cleaning or repairs. The rotor of an induction motor is inherently somewhat longer than that of a synchronous motor, because of the space required for the end connections of the coils on the former, and this necessitates a greater space for movement of the stator

The following table shows the relative base dimensions of the two types of motors, for several different ratings:

Rating			Floor Space: Synchronous Motor							Floor Space: Induction Motor						
H. P.	Rev. per min.	Cycles	Ft.	In.		Ft.	In.		Sq. ft.	Ft.	In.		Ft.	In.		Sq. ft.
9000	107	25	18	0	x	24	8	=	445	20	7	x	25	0	=	515
6500	187	25	17	5	x	15	7	=	272	16	7	x	19	3	=	319
5000	100	60	13	2	x	21	11	=	288	16	8	x	23	11	=	398
5000	240	60	13	8	x	14	2	=	195	14	0	x	16	0	=	224
5000	83	25	14	3	x	19	9	=	282	15	0	x	20	0	=	300
1500	300	25	10	10	x	11	8	=	123	12	3	x	11	9	=	143

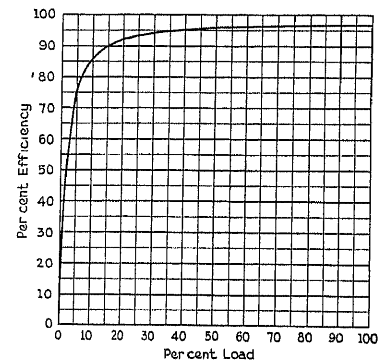

Fig. 9—Efficiency of 5000-H.P., 0.85-Power Factor, 240-Rev. Per Min., 2200-Volt, 60-Cycle Synchronous Motor from Test Data

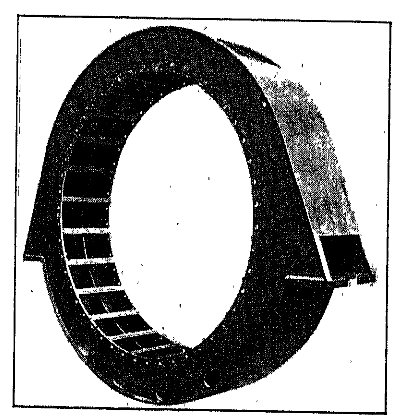

Fig. 10—Stator Frame Fabricated from Steel Plates and Bars

Speed Control

Control, or rather adjustment, of the speed of a synchronous motor in mill service is of course impractical, and its use must, therefore, be confined strictly to constant-speed mills. This fact also eliminates it from consideration on any so-called constant-speed mill on which a flywheel is necessary, for to get any beneficial effect from the wheel the speed must vary inversely with the load.

The fact that the motor runs at truly constant speed, except for what variation in frequency occurs on the system, is an advantage on some types of mills. For example, if the product from a continuous mill of the

type shown in Fig. 3 is cut into lengths by a flying shear, as it leaves the mill, the lengths will be more uniform if the mill speed is absolutely constant than if it varies slightly.

Cost

The cost of a synchronous motor, of the capacity used for main roll drives, complete with exciter and control, is usually less than that of a similarly rated induction

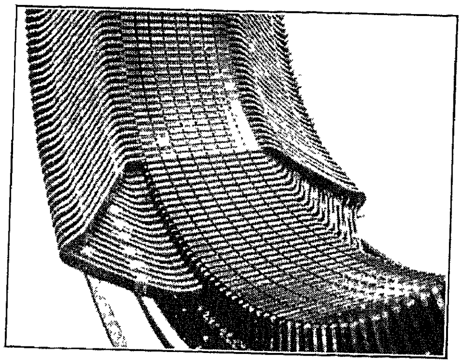

Fig. 11—Partly Wound Stator, Showing Method of Bracing the Coils

motor. For machines of medium capacities, speeds, and voltages, the differential is not great, but for large low-speed units, the synchronous machine is considerably less expensive.

Reliability and Ease of Repair

From the standpoint of reliability it can hardly be said that either type of motor has the advantage. A machine any more reliable than the well built mill-type induction motor has proved itself to be, would be difficult to find, but there is no reason why the synchronous motor should not have an equally good record in the years to come.

As far as ease of repairing is concerned, the stators of the two machines are practically on a par. The coils of the synchronous motor are somewhat larger and heavier as a rule, but there are fewer of them. The rotor of a synchronous motor could probably be repaired more quickly than that of an induction machine. The fact that the synchronous motor has a fairly large air-gap helps to facilitate the moving over of the stator for cleaning or repairs.

Construction

Obviously the details of design and construction described in the following paragraphs apply to motors built by the company with which the writers are associated. The practise of other manufacturers may differ in some respects.

The mechanical and electrical construction of the mill-type synchronous motor is fully as sturdy and reliable as that of the mill-type induction motor. The quantity and kind of the materials used are such that all stresses are kept within a conservative minimum.

The stator frames of the earlier motors of this type are of cast iron. Those built within the past year and a half, however, are fabricated of steel plates securely welded together and braced to form an exceedingly strong and rigid structure. To the inner periphery of the frame are welded steel dovetailed keys. The core laminations are held on these keys and clamped between heavy welded steel finger flanges. Air ducts are provided in the core and complete ventilation is further accomplished by the use of air-slide wedges.

Because of the size and weight of the stator coils in these large motors they are insulated very carefully to protect them from mechanical injury. After their assembly in the stator the end projections are securely laced to insulated steel bracing rings which are supported from the stator frame. The larger machines are supplied with resistance-temperature detectors. The stator coils are liberally designed to safely take care of sudden overloads or the condition where the motor may be required to develop its maximum torque as an induction motor.

The rotor spiders of the machines of small diameter are built up of laminations punched from heavy steel plates, those of larger diameter being of cast steel. The laminated pole pieces are either dovetailed into the punched rotor or secured to the cast rotor by means of bolts screwed into steel keys imbedded in the pole pieces.

The field windings are usually of edgewise-wound copper strip. Here again great care is given to the insulation between the turns of the winding, and of the coils as a whole from the pole pieces and rotor spider. One of the recent improvements in design consists in the addition of fins to the ends of the field coils which

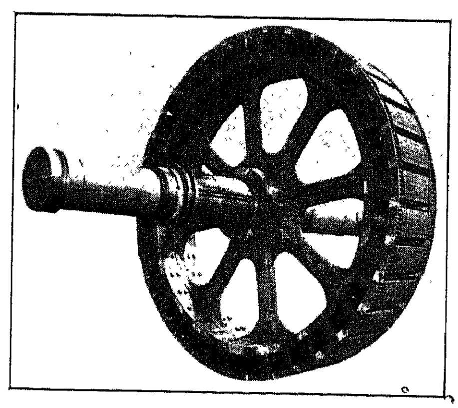

Fig. 12—Rotor with Cast Steel Spider

are made by simply projecting every second or third turn during winding. These fins provide an increased area of radiating surface on the ends of the coils and have proved very effective in reducing the field temperature.

Since, at times, these motors may be required to develop their maximum torque as induction motors, considerable attention is given to the heat storage capacity of the amortisseur winding, the materials

used being such that their strength will be retained at high temperatures. The bars are silver soldered into the end-ring segments. The end-ring segments have bolted joints between poles so that each individual pole may be readily removed from the rotor without disturbing the others.

The specially designed mill-type pedestals are securely bolted to both the base and foundation. They are equipped with babbitted thrust collars when this feature is desired. These pedestals are insulated from

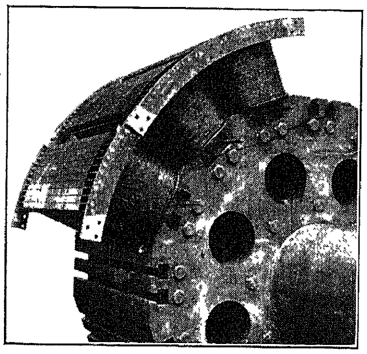

Fig. 13—Rotor with Laminated Spider

the base to eliminate the possibility of shaft currents. The spherical-seat, self-alining bearings may be equipped with temperature relays. A liberally designed ring oiling system insures ample lubrication but in addition, provision is made so that flood lubrication may be applied.

The base is provided with rollers under the carrier plates supporting the stator feet in order that the stator frame may be easily moved in a direction parallel to the shaft. The carrier plates are keyed to the base in order to maintain the alinement of the stator frame during this movement.

Air heaters may be installed in the lower halves of the stator frames of these motors to prevent the possible accumulation of moisture on the windings in case the mill is idle for any considerable length of time.

Control

A few main-roll synchronous motors are started at full voltage, but most of them are so large that such practise is not desirable because of the resulting demand on the power system. Consequently, an auto-transformer is usually employed to give reduced voltage for starting. For some of the largest machines it has proved desirable to employ two reduced voltage steps in the starting operation, and to meet this condition the combination Korndorfer and reactor method illustrated diagramatically in Fig. 14 has been developed.

The sequence of operations for starting, stopping, or plugging the motor is initiated by the simple movement of the handle of a master switch placed near the mill, and the operation is completed automatically under the control of relays on the control panel.

We will assume that the motor is at rest and that the operator throws the handle of the master switch to the "forward" position. Oil circuit breaker A closes at once, establishing the neutral connection of the auto-transformer,—F follows immediately, connecting the line end of the auto-transformer to the line and thereby applying the first step of reduced voltage to the motor. With this voltage the motor should start and gradually increase its speed.

When it reaches a predetermined speed, usually from 50 per cent to 75 per cent of synchronism, as indicated by the frequency obtained from a small pilot generator on the main motor, a relay operated in response to the frequency causes breaker A to open, and immediately thereafter breaker B closes. B connects the motor to the line through the reactor. The reactor is so proportioned that the voltage drop across it at the time it is connected in the circuit is sufficient to reduce the voltage at the motor to a value between the line voltage and that given by the auto-transformer tap. As the motor speed increases, the current will drop and the voltage at the motor terminals will rise.

When the motor reaches approximately 95 per cent synchronous speed, as determined by a relay which operates only when the difference between the line frequency and the pilot generator frequency is 5 per cent or less, field excitation is applied, of sufficient value to give approximately unity power factor. This pulls the motor into step, and so reduces the current drawn by the motor through the reactor that the voltage at the motor terminals increases almost to the line value.

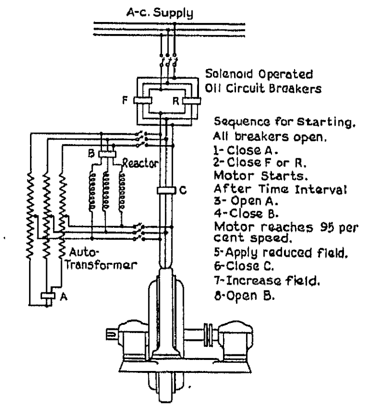

Fig. 14—Elementary Diagram of Combination Korndorfer and Reactor Method of Starting Synchronous Motors

After a short-time interval, breaker C closes, B opens, and the field excitation is automatically increased to the full value.

It will be noted that at no time during the sequence of starting operations is the motor entirely disconnected from the line. Furthermore, owing to the use of the reactor, the transition from the second starting voltage to the line is made with extreme smoothness.

Protection is provided against under-voltage, loss of

excitation, and failure to synchronize within a definite interval after the master switch is operated.

The control equipment for a synchronous motor involves more oil circuit breakers than does that for an induction motor, but the latter requires a number of large contactors and resistors for its rotor circuit, with relays for controlling the same. Neither is especially complicated in installation or maintenance. So far as the mill operator is concerned, he simply moves the handle on one kind of master switch to start either type of motor.

Installations

A considerable number of synchronous motors is now installed or being built for main roll service. Those supplied by one manufacturer include the following:

A 9000-hp., 107-rev. per min., 25-cycle, 6600-volt unit is driving a continuous sheet bar mill at the Cleveland plant of the Corrigan-McKinney Steel Company. This motor has a higher continuous horsepower rating than any other motor in industrial service in this country.

Two motors, one 6500-hp., 187-rev. per min. and the other 4000 hp., 83 rev. per min., 25 cycles, 6600 volts, form part of the drive of a continuous skelp mill at the Bethlehem Steel Company's Sparrows Point plant.

A 5000-hp., 240-rev. per min., 60-cycle, 2200-volt synchronous motor is being installed to drive a tube piercing mill at the Standard Seamless Tube Company's plant at Economy, Pa.

The Continental Steel Corporation, Kokomo, Indiana, has purchased a 5000-hp., 100-rev. per min., 60-cycle, 2200-volt motor to be used in driving a continuous sheet bar mill.

The Copperweld Steel Company of Glassport, Pa. will use three 60-cycle, 2300-volt synchronous motors, one 600-hp., 400-rev. per min., one 600-h. p., 514-rev. per min. and one 600-h. p., 900-rev. per min. to drive various merchant and rod mill stands.

Two 400-hp., 720-rev. per min., 60-cycle, 4600-volt motors have been purchased by the Higgins Brass and Manufacturing Company, Detroit, Michigan, to drive brass and copper mills.

Another manufacturer has built several synchronous motors for seamless tube mill service, some of them being for piercing mills and some for tube rolling mill drives.

Conclusion

The foregoing discussion, we believe, has made clear that the synchronous motor is a real competitor of the wound-rotor induction motor for some types of main roll service. The number of installations which have been made within a comparatively short space of time certainly proves this contention. The synchronous motor has certain definite advantages, such as better power factor, efficiencies, and cost, which make it very attractive. Its starting characteristics are not so good as those of the induction motor, but for many drives they are sufficient and on those mills it can often be used to advantage.

It seems safe to predict the widely increasing use of the synchronous motor in mill service, and with this prediction goes the hope that such motors will be applied, designed, and built only with a full knowledge of the demands of the load and the limitations of the motor.

Discussion

H. V. Putman: Mr. Berkshire classifies the application of synchronous motors to cold strip rolling mills as undesirable because of the high starting torque (usually 200 per cent) required. We already have one installation of a synchronous motor on a cold strip mill starting up under 200 per cent of normal torque and giving entire satisfaction.

The principal problem in applications of this kind is to obtain the necessary starting torque with a reasonable inrush kv-a. Recent developments in synchronous motors indicate that it is possible to obtain these high values of starting torque with little more inrush kv-a. than would be required by a normal wound-rotor motor.

As an example, we are now building a low-speed synchronous motor for driving a ball mill in a rock-crushing plant. This mill requires approximately 200 per cent starting torque and slightly over 100 per cent pull-in torque. This synchronous motor will deliver 200 per cent starting torque with about 390 per cent inrush. In fact, the starting torque may be varied at will from about 160 per cent torque to 235 per cent, the inrush being almost proportional to the torque. The calculated pull-in torque is 125 per cent.

Now this is almost as good torque per kv-a. as would be obtained from an ordinary slip-ring motor. While the slip-ring motor will give 100 per cent torque with 100 per cent kv-a. to get 200 per cent torque at starting it is necessary to reduce the resistance in the rotor circuit so that its power factor is much poorer. Also, it should be remembered that the normal kv-a. on which the per cent inrush is based, is figured on a power factor considerably less than unity, especially on low-speed machines. The slip-ring motor would therefore give 200 per cent starting torque with an inrush of about 350 per cent based on unity-power-factor kv-a. This is to be compared with the 390 per cent inrush for the special synchronous motor mentioned above. This leaves the slip-ring motor but little advantage for applications requiring high starting torque.

While some features of this new motor are still experimental, it may be said at this time that it is of the salient-pole construction and has the high efficiency and low exciter capacity characteristic of machines of this type.

In view of these recent developments, I think it is reasonable to predict that in the near future synchronous motors will be recommended and used for any constant-speed, non-reversing drive, regardless of the starting duty.

There are two other points I should like to comment on: the matter of power factor and the construction of damper windings.

I think most users of synchronous motors have the idea that unity-power-factor motors are cheaper than 80 per cent power-factor machines. This is ordinarily true, but it is not true of motors having a pull-out torque of between 250 per cent and 300 per cent. An 80 per cent motor costs no more than a unity-power-factor motor when the pull-out torque is between these values. Invariably the electrical manufacturer prefers to supply the leading-power-factor machine because it has a lower magnetizing current and hence better starting characteristics. Leading-power-factor motors are therefore to be recommended when high pull-out torque is required. When no corrective

kv-a. is required, then a 90 per cent power-factor machine represents a desirable compromise.

The best damper winding, judged from its heat-storage capacity, is one in which the damper bars are buried in the pole iron for their entire length, no portion being left exposed to the air. This is because practically all the heat is generated in the damper bars. They have small heat capacity in themselves, but when buried in the iron of the pole face the iron conducts the heat away from the bars into the pole body, where there is unlimited capacity for storing it during the starting period. Experience shows that a portion of the damper bars exposed to the air is the first part to fail when a damper winding is allowed to burn out

A 4000-hp. steel-mill motor now being built has a damper winding in which the bars are buried in the pole iron for their entire length.

B. A. Behrend: The use of synchronous motors for the driving of rolling mills is certainly greatly to be commended. The synchronous motor is more robust and less liable to breakdown and, when in need of repair, such repair is more readily and easily made. Its overload margin can be made at least equal to that of the induction motor; its power factor can be made anything required, leading or lagging; its speed can be made low as there is not the same difficulty in taking care of a large number of poles which causes the low power factor of the induction motor. On this point the simple rule which I gave years ago ("The Induction Motor," its Theory and Design, now available in a new edition as "The Induction Motor and Other Alternating-Current Motors," McGraw-Hill Book Co., 1927) might be useful to the steel engineers who are not familiar with the design of electrical machinery. This rule is: Maximum Power Factor $= 1:(2\,\sigma + 1)$, where σ is the leakage coefficient which is proportional to the air gap multiplied by a constant dependent on design and divided by the pole pitch. For 5000 hp. at 100 rev. per min. and 60 cycles there are required 72 poles which, with a rotor diameter of 15 ft., corresponds to a pole pitch of about 8 in. Given an air-gap of 1/16 in., a leakage factor of about 0.08 results. Substituting this for σ in our formula for the power factor, we obtain $(\cos\varphi)_{max} = 1:(1+2\times.08)$ or 0.86. Such motors have been built and the small air-gaps have operated satisfactorily but that is a different story from recommending them when other solutions are available. Next, the synchronous motors are more readily wound for high voltage and the stator windings are more secure for the same voltage; there remain as the principal difficulties the starting torque and the hunting in regard to which the induction motor is superior.

The starting torque of the synchronous motor could be raised by methods of pole face windings with resistance and slide rings but such motors have not been popular, a characteristic which appears to apply to most "combination" devices. There remains the alternative of employing clutches which allow easy starting and much will be done in this direction. There are in use abroad centrifugal pulleys or pulleys with centrifugal devices in them, which permit starting without load. Similar schemes will be used here as soon as the demand for them is going to be felt which will be in the immediate future.

Thus there remains the characteristic of hunting which can be overcome readily by calculating the natural period of oscillation of the synchronous motor at the excitations at which it operates and increasing or decreasing the mechanical inertia of the revolving parts so as to secure a coefficient of resonance which corresponds to a small increase in the amplitude of oscillation of the rotor. This assumes the knowledge of a period of forced oscillation which is not always capable of being estimated. It can be estimated in motors driving compressors, for instance. As the synchronous motor requires a powerful low-voltage winding on the rotor, this winding will act as a circuit in which the energy of oscillation can be quickly dissipated thus leading to a rapid decay of the oscillation without causing disturbance in the system. The summary favors preponderantly the synchronous motor over the induction motor for slow-speed low-starting torque, non-reversible applications.

F. C. Hanker: The following table gives practically a complete list of synchronous motors of 300 hp. and above installed annually to drive various mills in the metal industry.

Year	Hp.	Units
1913	500	1
1918	1350	1
1924	1600	3
1925	18100	13
1926	12000	3
1927	27100	17
	60650	38

The first main-roll electric drive installed in the United States was put in service in 1905, and by the end of 1924 the total electric hp. on main-roll drives was approximately 1,354,600, of which 3450 hp. was synchronous motors. Since 1924 the total hp. of electric motors installed for driving rolling mills has increased 42 per cent and the synchronous-motor hp. has increased 1750 per cent. At the present time the synchronous-motor hp. on rolling mills is approximately 60,000, practically all of which has been placed in the last three years.

A partial list of types of mills now being driven by synchronous motors follows:

Continuous sheet bar and billet mill
Continuous skelp mill
Piercing mill
Tube rolling mill
Tube rolling and sinking mill
Merchant roughing mill
Merchant finishing mill
Cold sheet mill
Copper rod mill
Brass and copper sheet mill.

In addition to the above, some smaller synchronous motors are being used for wire drawing.

Two or three of the above types are generally driven by wound-rotor induction motors in connection with flywheels. By properly proportioning the synchronous motor a successful application can be made on these mills, omitting the flywheel and using synchronous motor drive. This is, of course, only practical when the power system supplying the motor is of sufficient size that the mill peaks are not objectionable, as these peaks cannot be equalized if the synchronous motor is used. These peaks on the motor will increase the r. m. s. value of the load so there is needed a somewhat larger synchronous motor, than if a type utilizing a flywheel were used. This is partly offset by the decreased friction and windage losses incident to the omission of the flywheel.

It has been stated that the cost of a steel-mill synchronous motor is usually less than a similarly rated induction motor. Therefore, the fact that in some special cases a somewhat larger synchronous motor may be required to replace successfully a given size induction motor, does not seriously handicap the synchronous-motor installation from the cost standpoint.

The most recent application of a synchronous motor for rolling-mill service includes a 4000-hp., 2200-volt, 3-phase, 60-cycle, 450-rev. per min. unit for driving a continuous billet-roughing mill.

It would appear from the above that the author's prediction of a widely increasing use of synchronous motors in mill service is amply justified.

B. G. Jamieson: I should like to know why, in a recent installation of a large steel mill in Chicago, on which I understand several large manufacturers were consulted, a slip-ring motor was finally chosen, a 6000-hp. motor.

G. A. Chutter: (communicated after adjournment) The writers of this paper state that the synchronous motor is not adaptable to drives requiring reversal or speed adjustments. They further limit the field of the synchronous motor to drives not requiring a fly wheel, and exclude this type of motor from certain applications where the metal is cold-worked and the motors must be capable of starting under 200 per cent torque with metal in the rolls. Such drives are the cold strip mills and cold sheet mills. Approximately 90 per cent of the cold strip mills are driven by d-c. motors having a speed range of two-to-one, or greater. This speed range is necessary if the mill is to roll a wide variety of products, and the synchronous motor is barred from this field on account of its inability to supply this speed range, as well as on account of the high inrush kv-a. incident to the starting torque required.

In the case of the cold sheet mills there may be some possibility of applying the super-synchronous motor as described by Mr. Berkshire. This motor requires very little starting torque, consequently the stator may be brought up to speed with very small kv-a. inrush. The load is brought up to speed by applying a brake to the stator, so that a minimum peak demand is made on the line. This motor has the disadvantage of being somewhat more expensive than the synchronous motor, and having, in addition to the usual control equipment, a stator brake. This motor has given a very satisfactory account of itself in the cement mills.

Attention should not be diverted too much from the requirements of the major part of the field in which the synchronous motor is the logical contender, to a relatively small part of the field where its choice is more questionable. In the major part of this field, as outlined by Messrs. Winne and Berkshire, it is not so much what torque the synchronous motor will develop at full voltage as the torque per kv-a. that the motor will develop. Load curves similar to that shown in Fig. 5 of this paper will be found very satisfactory for most of these applications. Without drawing more than 100 per cent kv-a. we can have a starting torque of 58 per cent on the 41.5 per cent voltage tap of the auto-transformer, and a "pull-in" torque of 61.5 per cent at 100 kv-a. on the 75.5 per cent voltage taps of the auto-transformer. These torques are satisfactory and the motor may be connected to the line without exceeding 100 per cent kv-a. It will be noted from the data shown in Fig. 5 that the torque per ampere at starting is approximately in the ratio of 1 to 1.73.

W. T. Berkshire: I should like to corroborate Mr. Putman's statement regarding the cost of synchronous motors required to develop anything over 200 per cent pull-out torque.

We have found it true, also, that it costs no more to build an 0.8-power-factor machine than it does a unity-power-factor machine to develop this pull-out torque. This 9000-hp. motor to which I have referred was built for unity power factor wholly because of the customer's wishes. The power factor in his plant was very nearly unity and he did not want any leading power factor because it would mean just as much drain on his generating system as if the power factor were lagging.

In order to obtain the pull-out torque on this machine, the air gap was ⅞ in.

When speaking of machines required to develop 200 per cent starting torque, I had in mind the ordinary, straight synchronous motor as we usually understand it.

We have also built a number of smaller machines for cold strip and cold sheet mills of the super-synchronous motor type. In this type of machine, the stator revolves during the starting period. It is started as an induction motor with the stator revolving, and after the stator comes to synchronous speed and excitation is applied with the rotor standing still, the brake is applied to the outer periphery of the stator and the load gradually brought to speed. This machine, of course, can develop the whole of its pull-out torque throughout the whole of the starting of the load from initial start to synchronous speed.

We have never tried to apply this machine to motors having a range of 6000, 8000, or 9000-hp., but there is no reason why it should not be done. For that reason, I don't see why eventually we should not be allowed to drive cold strip mills with the synchronous motor.

The Chicago Regional Power System

BY E. C. WILLIAMS[1]
Member, A. I. E. E.

Synopsis.—This paper is a general description of the interconnected power systems in the region surrounding and including Chicago as a center. The electrical energy generated in this region in 1926 was over 4,000,000,000 kw-hr. and the combined generating capacity of the three largest companies was 1,340,000 kw. The paper outlines important features of major stations and transmission and distribution systems and gives plans for the future developments. It also explains the contract for interchange of energy among the three largest companies.

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THE design of any electricity supply system should be coordinated with the geographical, industrial and social character of the community which it serves. The electricity supply systems of the Chicago territory are in a rather unusual position in this respect because of the potential resources, both industrial and commercial, of the territory served. Chicago, due to its location, has been since the beginning in an excellent position to command an enormous growth. Being near the center of a great agricultural district with coal, ore, lime-stone, and other deposits close at hand, with excellent transportation facilities both by rail and water, it is not surprising that it has grown from a village of 4500 people in 1840 to a city with a population of 2,700,000 at the time of the last official census and now estimated at 3,700,000. The Chicago

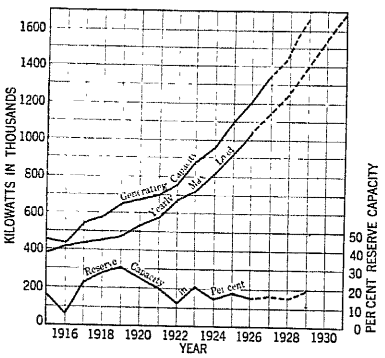

FIG. 1—GENERATING CAPACITY AND MAXIMUM LOAD IN THE CHICAGO REGION

Regional Planning Association estimates that by 1930 there will be a population of 4,891,600 within a radius of approximately 50 mi. of Chicago.

This industrial and commercial activity has created a demand for electric power which has been met by what has been called "the greatest pool of power in the world." According to the U. S. Geological Survey 73,791,064,000 kw-hr. of electrical energy were generated in 1926 by utility companies in the United States and 4,128,455,000 kw-hr. or 5.6 per cent were produced in the Chicago region.

The principal companies serving this area are as follows: Commonwealth Edison Company, Public Service Company of Northern Illinois, Northern Indiana Public Service Company, and Illinois Power & Light Corporation. The combined load of the three larger Companies, namely, the Commonwealth Edison Company, the Public Service Company of Northern Illinois and the Northern Indiana Public Service Company all of which are operated by the same interests has shown a growth in the last decade as shown in Fig. 1, the maximum load being below 400,000 kw. at the beginning of 1916 and being slightly above 1,000,000 kw. at the peak load period in 1926.

The stations of these three companies with their present capacities are shown in the following tabulation:

PRESENT GENERATING STATION CAPACITIES IN THE CHICAGO REGION

Commonwealth Edison Company		
Crawford Avenue Station	324,000 kw.	
Calumet Station	187,500	
Fisk Street Station	230,000	
Northwest Station	165,000	
Quarry Street Station	84,000	
Miscellaneous	65,060	
		1,055,560 kw.
Public Service Company of Northern Illinois		
Waukegan	110,000 kw.	
Joliet	50,000	
Blue Island	43,000	
Miscellaneous	34,790	
		237,790 kw.
Northern Indiana Public Service Company		
East Chicago	26,400 kw.	
Miscellaneous	20,425	
		46,825 kw.
GRAND TOTAL		1,340,175 kw.

GENERATING CAPACITIES TO BE ADDED IN THE NEXT TWO YEARS

1928	Crawford Avenue	100,000 kw.
1928	Powerton (Partly for use of Chicago Region)	52,000 kw.
1929	State Line	200,000 kw.

The Crawford Avenue Station with a capacity of 324,000 kw. is at present the largest station in the region and is capable of being developed to perhaps three quarters of a million kilowatts provided there is a certainty as to the amount of condensing water that can be depended upon from the Drainage Canal. A view of the turbine room of this station is shown in Fig. 2.

Another large generating station is the Calumet

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Station located on the Calumet River having a capacity of 187,500 kw. which is already utilizing about all available water in the Calumet River and has consequently reached its ultimate capacity. Other large stations in Chicago are the Northwest Station, the Fisk Street Station, and the Quarry Street Station which are older stations and on account of water conditions and property limitations can only be increased in size by the replacement of present units with more efficient units of larger size.

The main outlying stations are at Waukegan and Joliet with present capacities of 110,000 kw. and 50,000 kw. respectively. The site at Waukegan is capable of development to approximately 1,000,000 kw. The site at Joliet is capable of similar development providing the condensing water available from the Drainage Canal is not limited as mentioned in connection with the Crawford Avenue Station.

As to future generating stations which will furnish energy to the Chicago region two large ones are already

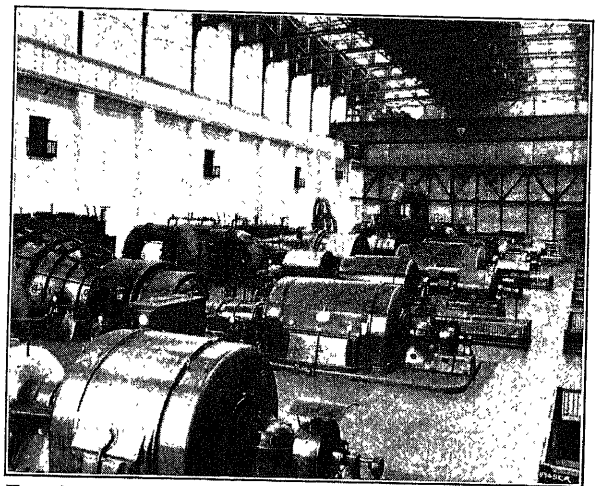

FIG. 2—TURBINE ROOM, CRAWFORD AVENUE STATION

under construction, namely the Powerton Station located southwest of Peoria near Pekin on the Illinois River and the State Line Station on Lake Michigan at the Illinois-Indiana State Line. Property has been acquired in Michigan City and also at a location southwest of Chicago on the Drainage Canal for the construction of future generating stations but it has not been definitely announced when construction will begin at either of these points. The Powerton Station is rather unique in that it is jointly owned by four companies which are the Central Illinois Public Service Company, the Illinois Power and Light Corporation, the Public Service Company of Northern Illinois, and the Commonwealth Edison Company. These companies have pooled their comparatively small requirements in the immediate vicinity and are erecting this modern efficient station. The first unit with a capacity of 52,000 kw. is scheduled for completion during the summer of 1928. In connection with this project a 132,000-volt transmission line is now being built from Joliet through Oglesby and Kewanee to the Powerton Station for interconnection with the Chicago pool.

With regard to the State Line Station, the tract of land procured is adequate and plans are being made for a station with an ultimate capacity of a million kw. or more. This station is to be owned jointly by the Commonwealth Edison Company, the Public Service Company of Northern Illinois, the Northern Indiana Public Service Company, and the Middle West

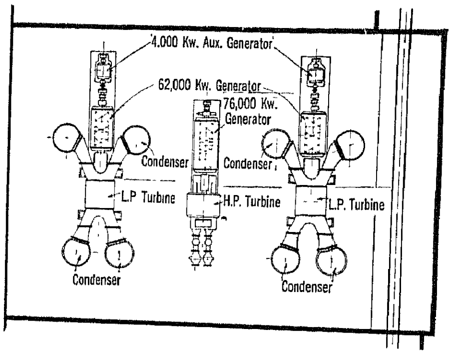

FIG. 3—UNIT NO. 1, STATE LINE POWER STATION

Utilities Company. The first unit, scheduled for completion in 1929, is to have a capacity of 200,000 kw. and will consist of three turbo generator sets each having a capacity of approximately one-third of the total arranged as shown in Fig. 3. Steam at 650 lb. pressure is admitted to a single high pressure turbine which exhausts into two identical low-pressure turbines each taking half of this exhaust steam.

In the design of this unit, means are provided where-

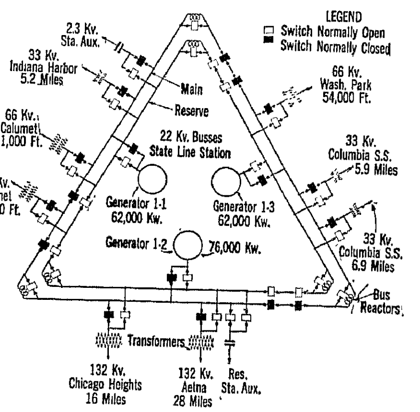

FIG. 4—BUS AND FEEDER CONNECTIONS, 1929 STATE LINE STATION

by any one of the three turbines may be taken out of service and the other two continued in operation thus overcoming the common objection from an operating standpoint of such a large capacity being contained in one unit. At present five such units of 200,000 kw. each are planned for this station with suitable transmission facilities for carrying away the energy. Contrast with these units, the 30,000-kw. units which were installed at the Calumet Station as late as 1921, which

were then the largest ever built for this territory.

The electrical installation also is rather unusual in that the generator bus will be completely out of doors and entirely enclosed by metal so that no physical contact can be made with any live parts. Fig. 4 shows the schematic arrangement of the bus which is a double ring bus divided into three sections, one generator supplying each section with suitable reactors and oil circuit breakers between sections. It is so laid out that as future generators are added one additional bus section will be placed in the ring for each additional generator. The generator voltage and consequently the bus voltage for this station is to be 22,000-volts which is somewhat higher than ordinary practise. The station is designed purely as a generating station and the energy will all be transmitted away in large quantities either at 33,000, 66,000, or 132,000 volts. No line busses are provided, transformers being installed integral with each individual line.

Another unusual electrical installation is to be found at Waukegan in the 12,000-volt "iron-clad" switchgear used in connection with the recently installed 50,000-kw. (58,825 kv-a.) unit. Although equipment of this type has previously been used in connection with lower voltage bus work at several substations in the Public Service Company territory, the Waukegan installation is the first used in a generating station in this country in connection with such a large capacity. The largest switches are rated at 1,500,000 kv-a. interrupting capacity and 3000 ampere carrying capacity. This

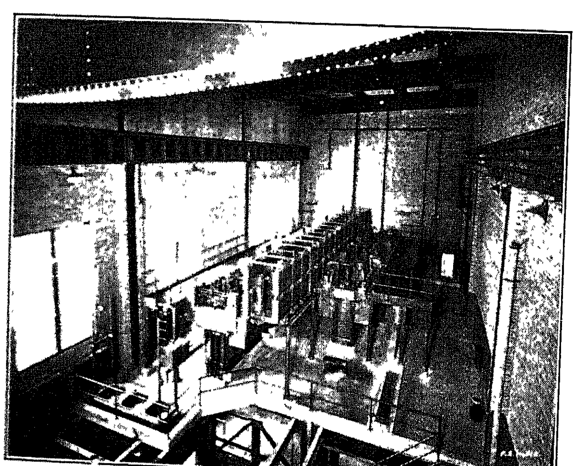

Fig. 5—Iron-Clad Switchgear on Generating Bus, Waukegan Station

installation which is indoors completely encloses in metal all of the bus work and switching equipment and thus reduces the hazard to operators in coming in contact with live parts as well as providing several other important advantages. This apparatus is very compact thus simplifying the building requirements both at the time of installation and at times when it is necessary to make additions or increase capacity. It is shipped in units or groups of units with practically all wiring, taping, and adjustments completed in the factory where workmanship and labor costs are naturally more favorable than in the field. Fig. 5 shows a view of this equipment.

In general this matter of switching equipment is becoming quite serious especially as to interrupting capacities. It would seem that the development of

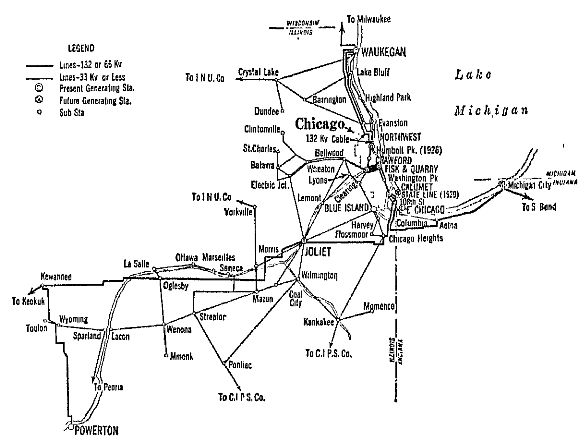

Fig. 6—Transmission System in Chicago Region as Proposed for 1928

high interrupting capacity switch gear has not kept pace with the growth of the business and consequently the requirements of the supply companies. The result has been that the supply companies have quite often been forced to make costly changes in structures as well as retire comparatively new equipment due to radical changes in design on the part of the manufacturers or unsatisfactory performance of equipment.

The transmission system in the Chicago region has had a very interesting development. Practically all of the stations have been interconnected. Within Chicago the system has developed from one 2250-volt transmission line in 1897 to the network of 12-kv. and 66-kv. underground cable of today. The outlying stations are either connected with each other or with the Chicago stations by means of a 132-kv. net-work with an auxiliary 33-kv. system. Fig. 6 shows the system as it will appear in 1928. It is to be noted that superpower interconnections have already been made with neighboring companies on practically all sides.

The transmission of large blocks of power through densely populated areas will soon require the extensive use of high-voltage underground cables. A move in this direction is to be noted in the six mi. of 132-kv. underground line connecting the Northwest Station in Chicago with the overhead transmission line from Waukegan at the city limits. This line consists of three single-conductor, hollow-core, oil-filled cables with a capacity of 90,000 kv-a. and has been in satisfactory operation since June of this year.

In this same connection there is still room for improvement in the design of overhead transmission lines,

especially in regard to mitigating the effects of lightning. Considerable progress in this respect however has been made during the last few years by the use of ground wires, arc-controlling devices, and the lowering of the plane of the conductors. The following tabulation summarizes the experience with ground wires in this territory:

EFFECT OF GROUND WIRE ON 132-KV. OVERHEAD LINE INTERRUPTIONS CAUSED BY LIGHTNING

Line		Interruptions				
No.	Location	Length miles	1924	1925	1926	1927
1.	Waukegan—Niles Center..	27.5	28*	20*	14*	0‡
2.	Waukegan—Northwest Station................	31.1				1*¶
3.	Waukegan—Kenosha......	20.7				0‡
4.	Joliet—Chicago Heights...	29.8		9	29	1‡
5.	Chicago Heights—108th St	14.4		7¶	7¶	6¶
6.	108th Street—Aetna......	26.7		0†‡	0†‡	1†‡
	TOTAL................	150.2	28	36	50	9

*Equipped with arcing-rings.
†13.8 mi. equipped with arcing rings.
‡Ground wire installed over circuit.
¶Ground wire installed over circuit on opposite side of tower.

The improvement brought about by the use of ground wires is conspicuously evidenced in the case of lines No. 1 and No. 4 where the ground wires were installed after some experience without them.

I wish now to refer to the "interchange energy contract" between the Commonwealth Edison Company, the Public Service Company of Northern Illinois, and the Northern Indiana Public Service Company by means of which an equitable interchange of energy and capacity is obtained. The capacity of all three companies is placed in a so-called "power pool" from which each company may draw in order to supply its load. The principal purpose of the arrangement is to enable the entire load of the three companies to be carried by the most efficient generators regardless of their ownership, leaving the less efficient to carry the peaks and to act as reserve. The energy is paid for by each consuming company at various rates depending upon the stations from which the energy is supplied. The investment charges are taken care of on a basis of demand and capacity illustrated by the following typical example. The figures given in the following tabulation show the generating capacity and previous maximum load for each company as of December 31, 1926, one of the monthly billing dates. The total generating capacity of 1,199,500 kw. is allotted to the three companies in the ratio of their previous individual maximum demands shown in the second column.

	Generating capacity 12-31-26	Previous maximum demand 12-31-26	Demand at time of system max. 12-15-26
Commonwealth Edison Co.	965,000 kw.	864,300 kw.	864,300 kw.
Public Service Co. of Nor. Ill..................	187,800	139,800	135,600
Nor. Ind. Public Service Co.	46,700	43,600	40,200
TOTAL.............	1,199,500 kw.	1,047,700 kw.	1,040,100 kw.

The company actually owning generating capacity, shown in the first column, in excess of its allotment receives the carrying charge on this excess from the other two companies which own less than their allotments. A limit of 20 per cent reserve on the total system is set up beyond which no credit is given.

I now wish to refer briefly to studies of the transmission network which are being made in the Chicago region. A plan has been adopted wherein the entire region including the City of Chicago has been divided into areas for distribution purposes. All the energy for each of these areas is to be supplied from one source. This source may be a generating station or a large or major distribution center receiving its supply over either 66,000 or 132,000-volt transmission lines. The energy is to be distributed at 33,000 or 12,000 volts from this main source to the various substations in the area for re-distribution. The substations in one area will not, in general, be connected to those of another

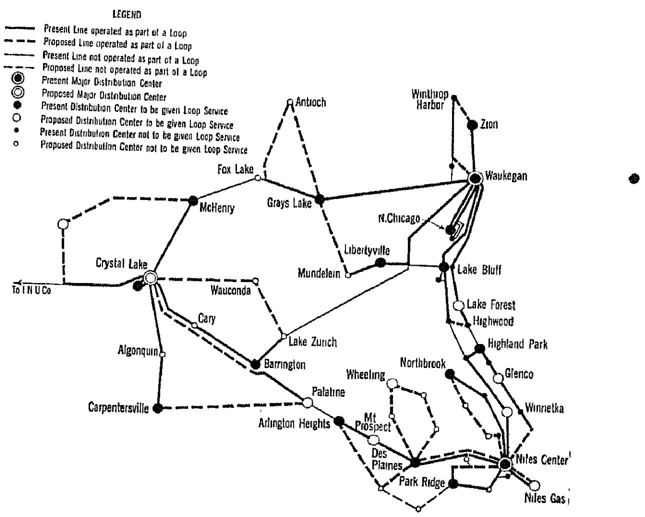

FIG. 7—PROPOSED 33,000-VOLT AREA TRANSMISSION SYSTEMS
Public Service Company of Northern Illinois, North Part of Territory

area although some emergency ties may be needed which will normally be operated open. With this system, the relay problem will be materially simplified and trouble may be more easily segregated than with the system in use at present wherein the various substations are connected to several sources. The duty on oil circuit breakers will also be considerably reduced. Fig. 7 shows the proposed scheme applied to a part of the territory of the Public Service Company of Northern Illinois. The high-voltage transmission lines supplying the major distribution centers are not shown. The groups of radiating loops from the major distribution centers conspicuously define the respective areas.

Fig. 6 shows two such major distribution centers planned for Chicago located at Washington Park and Humboldt Park to be supplied at 66,000 volts and scheduled for completion in 1928 and 1929 respectively. They are in addition to those already established at the

various Chicago generating stations. By 1928 the area surrounding Chicago will have several similar major distribution centers other than the generating stations, the most important of which will be located at Niles Center, Bellwood, Chicago Heights, Aetna, Michigan City, Oglesby, and Kewanee.

Transportation in the Chicago Region accounts for a considerable part of the demand for electrical energy. Of the 1,040,100 kw. total system demand which occurred December 15 of last year nearly 350,000 kw. was supplied to the electric railways in and around Chicago. The first and only steam road in this region to electrify is the Illinois Central Railroad which completed the electrification of its suburban service in June of last year. This customer's maximum demand to date has been 22,864 kw. The railroad operates its cars at 1500-volts direct current supplied by seven substations, five of which are owned by the Commonwealth Edison Company and two by the Public Service Company of Northern Illinois. The conversion to direct current is accomplished in some cases by mercury arc rectifiers and in others by units of two 750-volt rotary converters in series. Fig. 8 shows the Vollmer Road Substation at Flossmoor, installed by the Public Service Company of Northern Illinois for supplying this railroad and the light and power business in that vicinity. This particular substation was thought of interest inasmuch as it is located in a residential territory and in order to harmonize with the developments in that region a building of Spanish design which should not detract from the general surroundings was erected. The first impression might be that such a design is expensive but if the architect is ingenious in

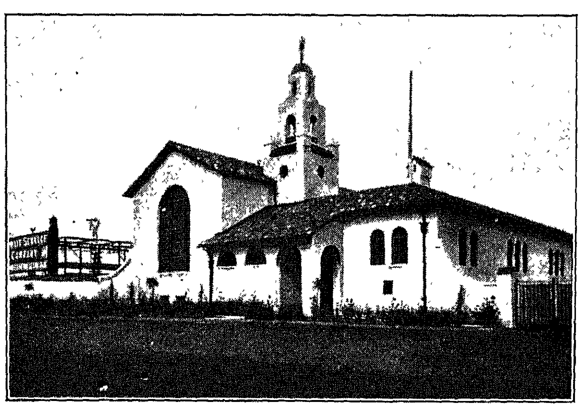

FIG. 8—VOLLMER ROAD SUBSTATION

the use of materials this need not be so. In fact the cost per cubic foot of content of this particular substation, was practically the same as that of another substation erected at the same time following the ordinary type of construction.

Fig. 9 shows the Glen Ellyn Substation supplying direct current to the Chicago, Aurora, & Elgin Railroad where harmonizing architecture was used again.

In this presentation I have tried to point out the problems existing in this region with the idea of bringing them to the attention of engineers generally as these problems are not peculiar to this locality but are being encountered in similar metropolitan areas. Engineers connected with power developments in such regions should be on the alert to so carry on system design that future demands may be met at reasonable cost and with a minimum of obsolescence.

It may be regarded by some as highly optimistic but

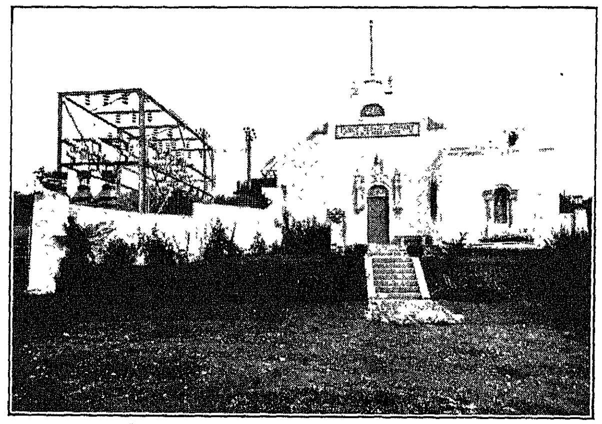

FIG. 9—GLEN ELLYN SUBSTATION

it is not inconceivable that sometime in the future the dictates of our customers may make intolerable the voltage dips and momentary interruptions due to lightning discharges and emergencies, the elimination of which we are prone to regard as insurmountable. It is to such problems that I commend the energy of the engineer for scientific study in order that the quality of service we render may continue to improve and that our system may be competent to meet the requirements of the public which are rightfully becoming more exacting year by year.

Discussion

H. B. Gear: One of the subjects which we have just heard discussed is one which has been a large factor in the development of electricity supply in Chicago. I refer to the interchange energy contract, which is in effect between these companies.

The unification of the power supply in the Chicago district did not become effective until the details of this contract were worked out. The effect of this contract is to permit these companies to work together in the development of their physical plant almost as if they were owned and managed by one company.

Before such a contract was in effect, each company tried to plan for its own reserve capacity and its own generating stations without great regard to the requirement or reserve capacity of its neighbors.

Under the operation of this contract no company proceeds to install any generating capacity without the knowledge of the other companies, and whatever is done anywhere within the district is done in view of the total reserve requirements of all the three companies in this district.

This, of course, makes it necessary that there be transmission-line capacity between the stations having reserve capacity and those having no reserve or a deficiency in capacity, in order that the large units installed at points where there is not enough demand to load them may be made available at those points where there is more demand than there is capacity to supply it.

This interchange arrangement is perhaps the most important feature described in Mr. Williams' paper.

J. L. Hecht: It seems to me that the problems in connection with a regional development of power system naturally divide themselves into two classes. One might be called the physical problems and the other the contractual.

So far, my own observation has been that the physical problems are the simpler. I feel that we are still in the infancy of this sort of development and there is a great deal to be done. One of the still unsolved physical problems is the one of placing the load on a large interconnected superpower system where we may want to place it. There has been discussion of installing at various points phase-displacement equipment, although up to the present time I don't believe there have been any developments along these lines. However, it appears that that problem will be taken care of.

With regard to the contractual problem, there are still many phases of the superpower contract problem to be worked out. While great strides have been made not only here but in other parts of the country in connection with the working out of contracts, I think that it is a matter to which the engineers should devote considerable thought so that advantage may be taken of their detailed knowledge of the problems that go with power-station and transmission operation.

Taking up another subject, I should like to refer to Fig. 1 of Mr. Williams' paper. I think one of the very important things brought out in that figure is the direct effect of a superpower system on the amount of capital that is tied up in reserve capacity. The lower curve giving the reserve capacity shows that in 1916 the curve was very low. We all know that was the result of war conditions. We were getting along without spending money, without installing necessary reserve capacity, and with taking a certain chance on "getting by." That was followed by a period of installing capacity with the result that the reserve ran rather high. Starting in about 1923, when the superpower interconnections were getting well under way in this region, the curve of reserve capacity became very much stabilized and for the six-year period following 1923 and running through 1929—because we know now what will be done in that period—the curve is almost flat. In other words, this curve illustrates the frequently made statement that having trunk-line interconnections between generating stations makes reserve capacity at any point available to the entire system.

T. G. LeClair: This question of interconnection brings up a number of problems which have heretofore not been given as much thought as they should be given.

One thing is that with the development of this large number of interconnecting lines we may sometime reach a limit as to how far we may go.

Mr. Williams in his paper made a statement that the development of switch gear is not keeping pace with the development of systems. This statement at present is quite true because with the development of systems and the development of the interconnecting lines we tie together capacities much more rapidly than we increase the load. We may for example add 50 per cent to the load while at the same time the amount of generating capacity which is tied together in one network may increase three or four times and consequently the interrupting capacity of these switches must be very much higher than it would be if it merely increased in proportion to the load.

So we have reached problems which become not only engineering, but economic, and I think these problems in the development of switch gear are up to the utility men as well as to the engineers of the manufacturers. If we go on developing switch gear with greater and greater interrupting capacities, it is quite possible for the manufacturers to do so, but by so doing they must increase the size and cost of this gear to such an extent that it may be much cheaper to separate the system into a number of parts than to go on paying more and more for this switching equipment regardless of the load it must carry. This problem first reaches us in the metropolitan areas where we have large capacities connected by short lines. As Mr. Williams mentioned, we have well over 1,000,000 kw. in Chicago, and the development of switch gear to interrupt this current is no simple question.

There remain two solutions. One of them is to separate the system into a number of small integral parts and sacrifice the benefits of reserve due to diversity between such sections, and the other is to develop a system which will not require an increase in size of switch gear due to the increase in capacity. To my mind, the second solution requires the development of a system wherein the fault current may be differentiated from the load current.

In the higher-voltage interconnections which we are just now developing, particularly in Chicago, the 66,000-volt cable, interconnecting stations must necessarily be single-conductor at the present stages of development. At the same time we can very rapidly make all our switching stations isolated-phase. By making the switching stations isolated-phase and transformers single-phase, and with single-conductor cable all system faults must begin as phase-to-ground and the fault current is then limited by the use of neutral resistors. By doing this we have made it possible to limit the fault currents on our proposed 66,000-volt system to slightly over 1,000,000 kv-a., while if we went on with the three-phase system, within the next five or six years we would have to interrupt between 4,000,000 and 5,000,000 kv-a. which would undoubtedly produce a problem for the manufacturers in the development of the switch gear. We have utmost confidence that they could develop this gear, but I doubt very much if we would be able to pay for it and consider our money well spent.

F. C. Hanker: I had not intended to make any comment on the particular point that Mr. LeClair raised, but in justice to the manufacturer we should consider the situation in connection with interrupting devices.

The operating companies, due to load conditions and the growth of their systems, have been forced to expand and interconnect and have concentrated energies far beyond what was expected when the equipment was originally installed. As Mr. LeClair says, devices of higher interrupting capacity can be built and are being built, but at higher cost. You cannot expect to control the increased energy released in a fault on a modern system and expect to control it safely with the small interrupting devices that were installed in the days when the stations were much smaller.

There is one other factor to consider. The operating companies should begin to consider the effect of the fault current on the operation of the system as a whole. If you can get the fault off a large interconnected system, such as in the Chicago region, in sufficiently short time to prevent the phase displacement of a different generating station or generating unit, then you can continue to supply the load without interruption. With the ordinary conditions we have today you have to interrupt the fault energy on the order of 0.2 sec. to avoid a displacement that is serious.

A number of companies that are operating interconnected are making plans to limit the amount of energy they can concentrate on their higher-voltage lines to a value of kv-a. on the order of 2,500,000. Breakers of that capacity are available in those voltages. Similarly on lower-voltage networks they have reduced that limitation largely for the reason that Mr. LeClair states, that there is an economic limit you can afford to put into switching devices.

You cannot continue to increase the generating capacity and the resultant energy in the fault and still expect your present interrupting equipment to care for the more severe service.

H. L. Wallau: The company with which I am associated makes it a practise not to parallel its 132-kv. lines directly. All such lines are paralleled only on the low-tension side of the transformers associated therewith. This has a marked effect on limiting the amount of power that may be developed in the

case of a fault and of reducing the duty on the circuit breakers which have to interrupt this fault.

B. M. Jones: The remark someone made about the details of the contract for interconnections was brought out very clearly in our company a year or six months ago.

We had a tie with the West Penn Power Company, our neighbor, and six months or so later we tied in with another company. The second tie was purely to carry a block of load, the plan being for one company to shift the load to the other company and not actually to tie in.

After the tie was made we found it would be advantageous actually to operate tied in together. It quickly developed that the second company we tied to was being penalized very severely due to the energy that flowed through its system to the next system and circulated back, a triangle of interconnection, and it involved such an amount of money that we couldn't tie together. We had actually to transfer the load.

When we first went into this second contract nobody had any idea that it would be worth while to tie together, and it just brings out the fact that the details of the contract must be watched very closely and all possible conditions anticipated.

E. C. Williams: Considerable comment has been made relative to awkward situations which have arisen due to the lack of coordination between the power contracts and the engineering principles which really dictate the operation of networks. The development of these superpower networks has been so rapid that all of the fundamental characteristics have not been readily recognized. It is the duty of the engineer to appreciate those characteristics and familiarize those people who negotiate these contracts with the importance of such coordination.

The temptation to temporize with the oil-circuit-breaker problem by resorting to breaking up the network into smaller networks and arranging transformers so as to increase the impedance of the circuit, is quite natural. However, the development is still quite young and it may be rather early to start such temporizing. If the development continues at the present rate in a few years we will face the same problems in the smaller pieces of the present network which we now face in the main network itself. It also must be recognized that the breaking up of any network brings with it certain operating disadvantages and interference with the free flow of energy which may affect the division of load between stations and perhaps the cost of production. As in all engineering problems it will no doubt be necessary to effect a compromise but in doing so the engineer should realize the limitations of such compromises and be prepared to take the necessary step in the development when it comes.

The Hall High-Speed Recorder

BY E. M. TINGLEY[1]

Associate, A. I. E. E.

Synopsis.—A new form of oscillograph for recording fault currents and their voltage disturbing effects in electric power systems is described. Representative records are analyzed and further applications of the instrument are suggested.

Introduction

LIFE histories of electrical disturbances in the extensive 60-cycle, 12,000-volt systems of the Commonwealth Edison Company have been written during the last few months by the high-speed recorder developed by Chester I. Hall. The object of this paper is to describe the application of the device and the records obtained with only a limited reference to the details of its construction.

Description of Recorder

This instrument is a form of oscillograph for tracing continuously the maximum values of current and voltage during system fault conditions. Sturdy construction makes it suitable for application in generating stations and substations. It seems to be the only instrument yet developed for this class of service. Its performance lies between that of the standard oscillographs and the switchboard curve-drawing meters with speed-up attachments.

The measuring element or meter is of the saturated magnetic-vane type, having a natural period of vibration sufficiently high to attain full deflection always in the same direction in each half cycle of current measured, and the motion is practically dead beat. The envelop of the maximum deflections is therefore a measure of current or voltage.

Four meters, three for voltage and one for current, are inclosed in a light-tight case, and the records are made on a flat stationary, 11-in. by 14-in., superspeed photographic film.

The optical system consists of an automobile lamp with reflectors and lenses for concentrating light beams on the mirrors of the oscillating systems from which they are reflected to a movable plane mirror, which in turn reflects them to the photographic film. The plane mirror traverses the light beams across the film, giving a time scale to the records of 1 in. per sec. The traversing mirror is operated by a phonograph spring motor through suitable gearing.

A starting relay, dry batteries for the lamp, transformers for the current and voltage meters, and alarm and signal circuits complete the installation.

Under fault conditions, the relay connects the measuring elements to their transformers, lights the lamp, and starts the light-traversing mirror. The starting operations require 1/10 sec. or less. At the end of the record, which continues for 10 sec., the measuring

1. Commonwealth Edison Company.

Presented at the Regional Meeting of District No. 5, of the A. I. E. E., Chicago, Ill., Nov. 28-30, 1927.

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elements are disconnected from their operating circuits, the lamp is extinguished, and the alarm is sounded.

Application

The Hall recorders as applied to the Commonwealth Edison system are installed in generating stations. They are started by fault currents to ground, and they measure this current and the three-phase voltages to ground. As faults invariably go to ground, the maximum information is obtained from a minimum number of recording elements.

The Commonwealth Edison 60-cycle, 12,000-volt system consists of four large separate systems, Crawford, Calumet, Fisk, and Northwest. Each unit system consists of a generating station with radial distribution cables to the substations. The neutral of one generator in each station is grounded through a 3-ohm resistor which limits ground-fault currents to about 2000 amperes. There are several hundred miles of 3-conductor cables in each 12,000-volt distribution system with only a few short overhead or open lines.

The generating stations are usually coupled only through their transformer lines so that a ground fault in one system does not cause ground current in another system. However, Fisk and Crawford are occasionally conductively coupled at 12,000 volts, and with this condition a fault causes neutral current at both generating stations.

The relays were first adjusted to trip with 125-amperes neutral current, but so many transient currents of undiscoverable origin operated the recorders without leaving a record that all the relays were readjusted to trip with 400 amperes. Transient currents were probably caused by synchronizing operations or the starting of transformers or motors.

The rather high condensive coupling to earth by the cables of the distribution systems may possibly be responsible for some of the neutral transients.

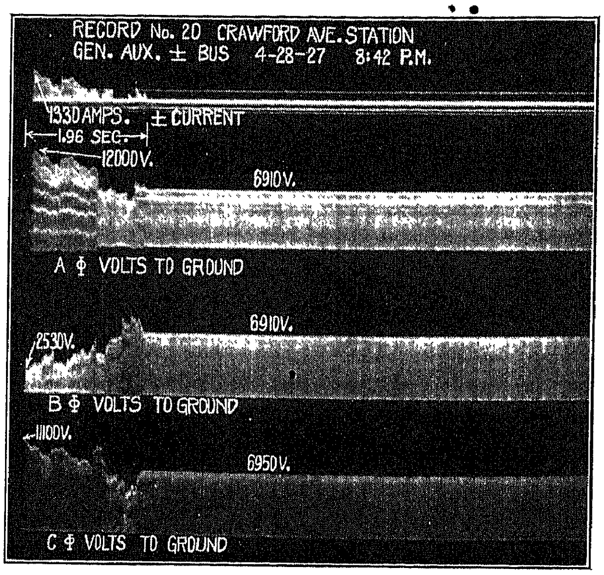
More than 100 records have been obtained, but only a few representative forms can be shown and described. They are necessarily a "behind-the-scenes" view of some of the accidents and failures incident to the operation of a great power system. However, very few of the failures recorded interrupted service.

The following paragraphs describe the faults recorded on the records shown in the corresponding illustrations.

Record No. 20, Crawford Station

Lightning on an overhead line started this fault. The *B*-phase was first affected after which the arc extended to the other phases in an irregular manner. The short period of zero neutral current may have been due either to the effect of a three-phase arc or to the momentary complete extinguishment of the arc. The opening of two circuit breakers, indications of which are lost in the arc irregularities, relieved the system of this fault.

The excessive voltage disturbances shown are with respect to ground only. The delta or phase-to-phase

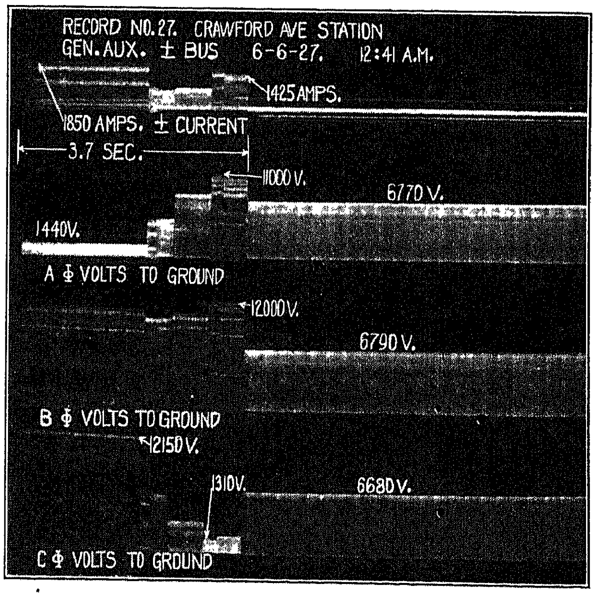


voltage at the generating station is affected only slightly.

The disturbance pattern is characteristic of a long flaming arc in air.

Record No. 27, Crawford Station

This is an unusual case of two simultaneous single-



phase failures to ground on separate cable lines. One failure by distortion of the system voltage with respect to ground precipitated the second failure and four circuit-breaker openings were required to clear the two

faults. Note that there are seven different steps in the neutral ground current. One of these is probably due to arc variations.

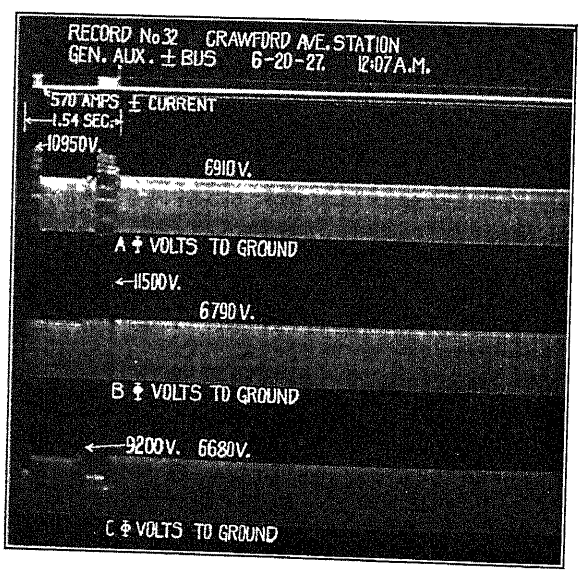
The first failure is on the A-phase and the second on C-phase. The abrupt increase of current at the beginning of the second fault is characteristic, as practically all records show that cable faults attain high current values very quickly.

The horizontal lines and patterns within the records are due to multiple reflections in the optical system. The vertical bands are caused by slight irregularities in the gears which drive the mirror that traverses the light beams.

A small allowance in the time scale is made for the starting time of the recorder.

Record No. 32, Crawford Station

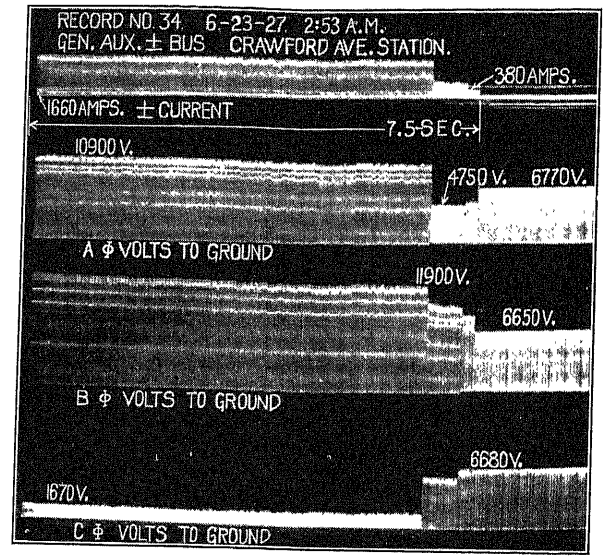
A three-phase cable fault produced this diagram and inspection of the burned cable indicated that the fault probably started between two phase conductors



and burned some time before going to ground, as the small time and small ground current indicated by the record do not account for the extent of cable burning. Zero value of neutral current during the first second of the record may be due either to a three-phase arc, or to the entire extinguishment of the arc. The fault was cleared by the operation of two oil circuit breakers, the effects of which are lost in the irregularities of the currents.

Record No. 34, Crawford Station.

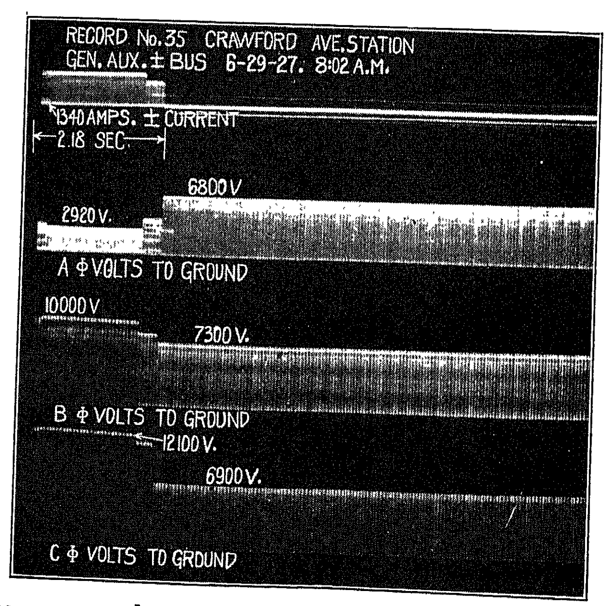
This record started with a C-phase cable fault to ground which extended to A-phase after 6.71 sec. The circuit-breaker relays were slow to respond to the ground-fault current, but the fault was quickly cleared by three circuit breakers after it developed to include another phase. As there are indicated only two steps in the neutral current reduction and three circuit



breakers operated, it seems that two breaker openings were simultaneous.

Record No. 35, Crawford Station

This is a usual fault to ground in one phase of a cable that was relieved by two circuit-breaker openings. The rounded corners in the current cut-off may indicate arcing within the circuit breaker. That the A-phase only is involved in the fault is shown by the reduction of the voltage of that phase to ground, and the increase of voltage on the other two-phases. This may be other-

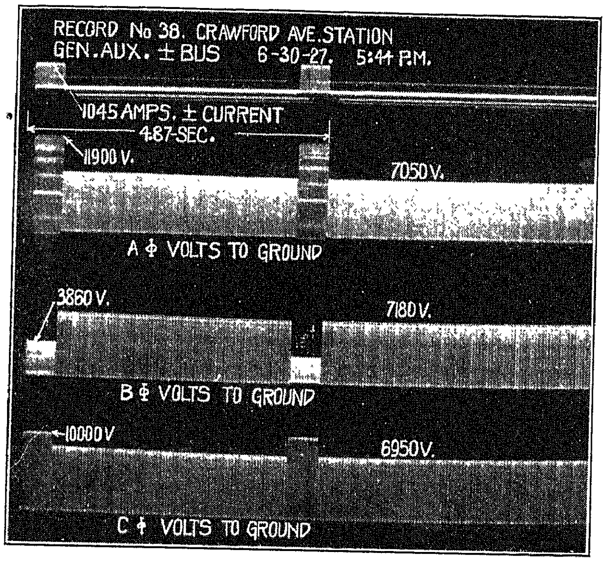


wise expressed as the displacement of the neutral point within the delta or as the tendency of the system voltage diagram to stand on one corner.

Record No. 38, Crawford Station

This record was made when system voltage was applied to a faulty cable. It is usual to make a ground test on a faulty cable by applying full system voltage on each phase singly by closing the disconnect and then

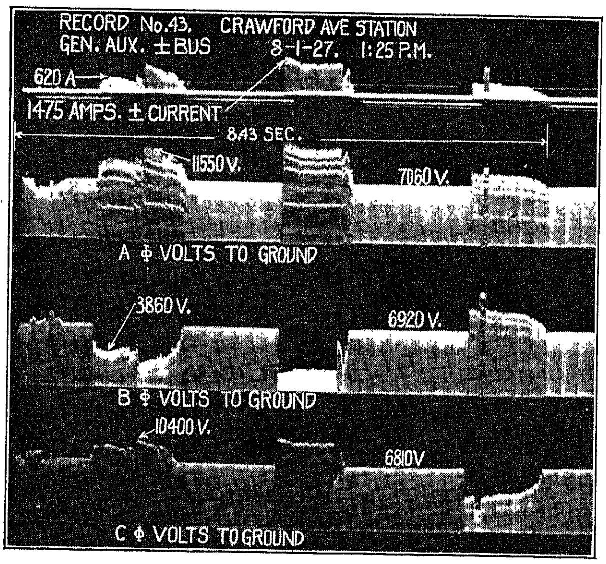
closing the oil circuit breaker. In this case, the circuit breaker was closed twice on the faulty phase, *B*, possibly through the defective action of the circuit breaker. Uniform closing and opening speeds in the circuit



breaker are indicated in both cases. This is an example of the way in which the Hall recorders furnish checks on the condition of apparatus and on its correct operation.

Record No. 43, Crawford Station

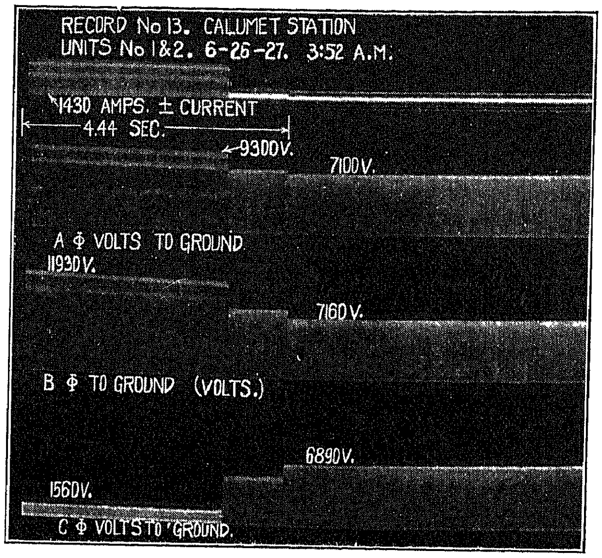
This trouble was caused by the leakage of brine on transformer bushings in an ice plant. Four bushings broke down. Two circuit-breaker operations were required to relieve this fault which may have extended beyond the 10-sec. limit of the recorder. The fault



seems to have started with small arcs on all three-phases and then ceased entirely, after which it concentrated on the *B*-phase and then on the *C*-phase. The irregularities in current and voltage are those of long arcs in air.

Record No. 13, Calumet Station

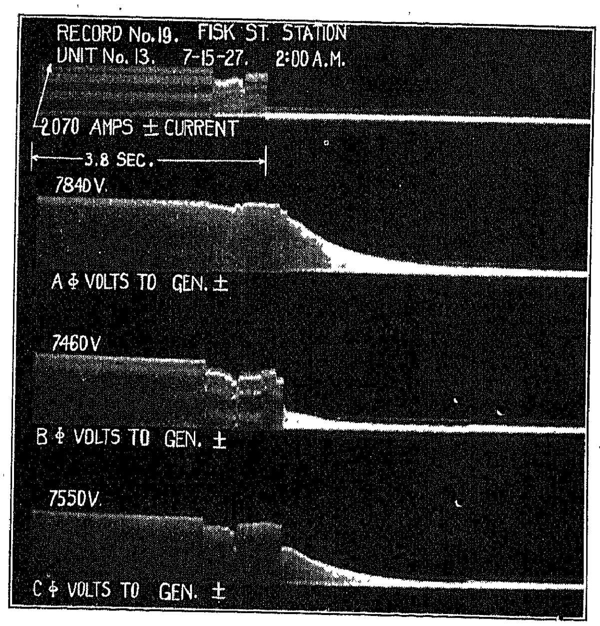
The steady current effect of the single-phase fault in the cable is again shown. The first and greatest reduction of fault current is caused by the opening of the circuit breaker at the generating station and the



final interruption is at the substation end of the cable. The fault current burned one cable conductor entirely in two. Small oscillations on *B*-phase voltage indicate that some synchronous apparatus may have been disturbed at the time the first breaker opened.

Record No. 19, Fisk Station

This most remarkable record of the series shows two cable failures and a generator winding failure, all to ground. In addition, there are three oil circuit breaker



operations and the opening of the generator-field circuit breaker, and the resultant dying down of the generator voltage. In this particular installation, the voltage is measured to the generator neutral and not to ground;

consequently, the voltage distortion registered is small.

It is possible to determine the time sequence of only a few of the events. The record started with a high neutral current due to B-phase cable fault, as the voltage on this phase is low. After about three seconds the C-phase was involved. The resulting voltage disturbance caused the generator winding to break down, which was quickly cleared through the action of the balanced differential relays. The relays also opened the generator-field circuit breaker and the generator voltage died down. The fault persisted on the B- and C-phases of the generator as indicated by the low voltage on these phases, and the higher voltage on the A-phase.

Starting Characteristics

In the generating stations as the recorders are started by neutral ground currents, a fault between phases does not start the recorder until shortly after it develops into a ground fault. Important parts of some faults are therefore lost. It has seemed impracticable to arrange a relay for starting on excess phase currents, as ground-fault currents are usually small and become lost in the load currents. Also, it is impracticable to start a recorder in generating stations by phase voltage reduction, as this is usually small. Starting on neutral ground current is the best compromise that can be effected.

It has been proposed to install recorders in some substations where the effects of voltage disturbances are important. A quick start may be made here on voltage reduction between phases, where it is important, but there will be no response to phase-to-ground distortions such as are measured at the generators. More complete information will be obtained through two sets of records, one at the generating station and one at the substation.

Records are frequently lost through the improper handling of the film holders and two separate sources of records furnish a good insurance against complete loss in important cases.

Use in Testing

Recently during oil circuit breaker testing, the recorders were found very valuable in measuring effects of the test currents on the system. The long time scale allowed the starting of the instruments through telephone orders just before the test currents were applied. There were, therefore, no lost intervals such as occur in automatic starting. Both generator and substation voltage disturbances were accurately measured. Such information is very valuable where synchronous apparatus or induction motors having no-voltage releases are liable to be shaken off the system due to momentary voltage reductions because of testing or fault currents.

General Comments Regarding Records

Records are not used to locate or identify system faults. This is better done by methods that were used before the recorders were available. Faults are located, inspected, and repaired long before the films are collected and developed. Usually there is a good agreement between the Hall records and inspection reports regarding the phases affected and other details so far as they may be interpreted. Normal faults to ground in cables and resulting breaker operations are rather uniform in performance. Departure from a normal characteristic calls for explanation regarding circuit-breaker relay operation, and in this way the records are of great value in checking the operating condition of such apparatus.

The effectiveness of the isolated-phase principle in generator station design has been fully demonstrated and recorded. On one occasion a single-phase arc to ground on the Crawford bus burned for 2¼ min. without affecting service. The first four seconds of fault produced a record at Fisk Street through a temporary 12,000-volt tie. The remainder was obtained from the speed-up charts.

Discussion

C. I. Hall: The figure in this paper "Record No. 43, Crawford Ave. Station," is one of the most interesting records. It shows such extreme changes of energy conditions that it must be quite obvious that such variations will set up high-speed transients and cause real difficulty in a central-station system.

Mr. Tingley indicated one factor which is of great interest, namely, the total time lag of the relay to get into complete operation after the occurrence of a fault.

The starting operation really consists of two parts: first, the operation of the high-speed relay, and, second, illumination of the light source. The time lag of the high-speed relay, of course, varies with the percentage of load above the critical value for which it is set. These loads vary but in the average case we have found that they are in the order of 500 to 1000 per cent of the setting of the critical value of the high-speed relay. At 500 per cent load on a 60-cycle system it requires 1.5 cycles to get the mechanism connected to the line. Then the time lag of the optical system is 2 cycles. This gives a total of 3.5 cycles. At 2000 per cent load the total time is about 2.3 cycles.

This device in constructed in other forms to meet special conditions. In one form the film moves upon the occurrence of the first short circuit for 10 sec. and then stops provided the short circuit has been opened, but is in condition to restart the instant another fault occurs, and so on, for a total of four. On the other hand, if the fault continues over the period of 10 sec., then the record will continue and give a total of 50 or 60 sec. of record.

Other forms have been constructed in which the chart is stationary, giving merely maximum values.

B. G. Jamieson: This materialization of a device which tells of these transient or semi-transient conditions characterized as faults is of the highest order of importance because it provides a medium for an inner discernment of the mechanism of cable breakdowns at least during the period between their inception and their retirement from the system.

The point I want to make has not been stressed this morning, and is the real point of reference in which our interest is centered. We have said, and Mr. Hall has just said very cautiously, that we needn't expect, or we are not justified in expecting a device which anticipates a fault. Perhaps we don't need it. But we should like to know what happens from the instant (if that word applies) of the development of the fault. I think Mr. Hall really knows how that could be accomplished; that is, how the

time lag of the device, which was not emphasized but which is very vital in the operation of this instrument, can be controlled. Whether he does or not, it seems to me that the great value of this device as now constructed lies in the fact that it shows not only the data the author gave, but it shows the impotence of relay systems of the conventional order which are unable to function during the fault inceptions, considering the responsibility that is centered upon them in the development of our interconnected systems.

The idea of having a fault developed and prolonged for from eight to ten sec. with all protective apparatus absolutely helpless, taking no cognizance of it, seems almost ridiculous. It isn't that we want to anticipate the fault, but what we want is action in that incipient period and before fault current reaches a magnitude and a rate of propagation that is beyond the power of interrupting devices built or that can be built to cope with it.

What we need is a relay which will take cognizance of that fault in its incipiency. Our problem will be intensified by the prospect of oil-filled cables. If we are going to have oil-filled cables and we attempt to handle faults in this incipient period, I don't know how we are going to find the faults after we retire the cable. Perhaps someone can tell us that, but in any event it must be apparent that we now have within our grasp a device that enables us to concentrate on that important function of retirement of a faulty member before conventional types of relays wake up to the fact that there is trouble.

F. C. Hanker: The need of recording equipment that would function during transient disturbances on a power system has long been recognized. Operating companies have been badly handicapped by the lack of information regarding the sequence of disturbances, the values of power surges, the voltage and current conditions during faults that has made it impossible for the engineers to analyze conditions and apply remedial measures to prevent a recurrence of similar difficulties. It is encouraging to find a number of systems are equipping important stations with oscillograph equipment that will furnish records of transients occurring during normal operating conditions.

Mr. Tingley has outlined his experience with one type of recorder and shown the value to the operating company of this sort of record. I cannot let his statement that this is the only instrument yet developed for this class of service go unchallenged.

There has been installed on the system of the Southern California Edison Company a number of automatic recording instruments for over two years. These include 3-element oscillographs, single-element oscillographs, or osisos, special reflecting-type high-speed average wattmeters both single and polyphase, and high-speed dynamometer-type graphic meters. A report of the results from these devices was presented before the Pacific Coast Convention, A. I. E. E., held at Del Monte in September, 1927.

When it is recognized that these instruments have been in service under the control of the operating organization for a period in excess of two years and that during that time not a single oscillograph element has been burned out, we feel we are amply justified in maintaining that this class of equipment is sufficiently rugged for practical operating conditions. I feel that a considerable amount of prejudice to the use of oscillograph equipment was due to the early experience with the original instruments using an arc lamp as the illuminant. I can well recall personal experience with such equipment in the field where practically laboratory experience was necessary to secure satisfactory records.

These conditions, however, have been changed as a result of the development of the portable type of oscillograph with improved galvanometers and incandescent lamps as the illuminant. This development has made the automatic use of this instrument possible.

The analytical studies on power system operation initiated by the Westinghouse engineers in 1921 led to a number of shop and field tests. It was early recognized that records of power surges were absolutely essential to give us the fundamental data necessary in our analytical studies. This led to the attempt to obtain records by modifying existing types of graphical instruments. The natural period of the electro-mechanical oscillations of the ordinary power system varies from ½ sec. to 1½ sec. depending on the size of the system and conditions of load so that it was felt that satisfactory results could be secured by improving existing types of equipment. We were able to obtain time constants of approximately 1/10 sec. with these modified devices but at the expense of a very considerable input to the coils.

It may be of interest to review the progress of the development of these devices as the need for them was indicated during the various field tests that were made to investigate the operation of power systems.

In the first series of tests made on the Pacific Gas & Electric system in May, 1924, an attempt was made to obtain information on the power oscillations by carrying static tests to the limit and recording the readings of the ordinary meters that were available. In addition oscillograph records were taken of current and voltage conditions. The second series of tests was made in January, 1925, during which records were taken of staged short circuits. Oscillograph records of current and voltage were taken and in addition the experimental dynamometer-type graphic meter previously mentioned was used. In an effort to analyze the power surges the oscillograph records were enlarged on a screen and the energy oscillations calculated. It was found in this analysis that the application of the usual form factor to current and voltage waves did not check with the analytical work by some 30 per cent. This led to a further study of the records and it was found that the wave distortions of current and voltage during the transient period were so great that it was necessary to integrate the actual wave forms to get reasonable comparisons between test and calculated results.

The next step in the development of recording equipment was during the tests made on the same system in June, 1925, where reflecting type average wattmeters both single phase and polyphase, having time constants of 1/20 sec. were used. By the use of the optical system considerably greater magnification of angular deflection could be obtained so that usable records with permissible volt-ampere burden were possible.

It was following these tests that the recording equipment was installed on the system of the Southern California Edison Company for the purpose of securing records during actual operation. The staged tests made on the system of the Pacific Gas and Electric Company gave very important data that was extremely useful in substantiating the analytical work previously carried on. It was recognized, however, that it would be desirable to obtain records under actual operating conditions on a system and it was for this purpose that the installations on the more important generating and substations of the Edison Company were made. The results of two years' experience were presented before the Institute in September, 1927, as mentioned previously, and the value of this type of apparatus as an aid in analyzing system operation is evident by the installation of 9-element oscillographs arranged for automatic operation in the new Long Beach generating station. It is also the intention to install similar equipment at the new high-tension substation under construction.

In the last series of field tests made on the Pacific Gas system in June, 1926, a still further development in watt-oscillographs was used. This was the single-phase instantaneous type galvanometer using the bi-filar element for voltage and substituting an electromagnet wound for current for the permanent magnet. These devices have been used in numerous other field tests and have proved their value. Using the standard suspension these elements have a natural period of 4000 cycles per sec. so that

they are of sufficient sensitivity to record the more important harmonics that might affect the results. It was recognized that the polyphase element of this type was desirable during the transients in order that the polyphase oscillations could be recorded. Under unsymmetrical short circuits without using any sequence network the record of the single-phase element could not be utilized directly. This difficulty is overcome by the development of the polyphase instantaneous element.

The use of the oscillographic type of equipment enabled us to record accurately the results even with greatly distorted wave forms that occur during transient operation.

In conclusion I feel that the operating companies should cooperate to a greater extent in the installation of recording devices as information of this character is necessary for the engineers to analyze fully the operation of the larger and more complicated power systems. We have been able to operate satisfactorily in the past where systems were comparatively simple and the requirements for continuity of operation were not so rigid. With the great extensions of the interconnections and the increasing size of systems it is necessary to make every effort to keep down the plant investment so that a reasonable return on the capital is possible. This makes it necessary to operate the facilities at more nearly their limits so that it is much more important to know just what these limitations are in order to determine the factors of safety that are permissible. The conditions now existing in the Great Lake region where you have great concentration of power in such a small area will soon spread to other parts of the country, making it of increasing importance to have a fuller understanding of the operation of a system under fault conditions.

Herman Halperin: In connection with Mr. Jamieson's discussion of a device in combination with a switch to cause the switch to disconnect faulty apparatus before the failure current becomes too large, which, I presume, would be at least a few hundred amperes, he stated that there might be considerable difficulty in locating the failure in an oil-filled cable when only such a small fault current was allowed to flow.

Experience with testing 132-kv. oil-filled cables in our laboratory indicates that there should be no great trouble in locating such faults. In an accelerated life test on oil-filled cable a failure occurred in the cable but did not burn a hold through the sheath. It is estimated that the failure current (furnished by the testing transformer) was only 35 amperes and that it flowed for 0.3 sec.

In order to reduce suitably the fault for location, it was necessary to go up to only 185 kv. with a d-c. kenotron cable-testing outfit at Northwest Station. The reducing current used was only 0.2 ampere. This outfit, however, is rated at 400 kv. and may be reconnected to supply 2 amperes at 50 kv. For field conditions, where the fault would cause a hole through the sheath of the cable, oil would flow through the fault out of the cable. For such conditions it may be necessary for final fault reduction also to use a d-c. supply of 1000 to 9000 volts and with a current capacity of 6 to 15 amperes to carbonize properly the fault in order that it may be readily located by the ordinary methods. Nevertheless, it does not appear that there will be any great difficulty in the location of such failures.

The Application of Relays for the Protection of Power System Interconnections

BY L. N. CRICHTON[1] and H. C. GRAVES, Jr.[1]

Member, A. I. E. E. Associate, A. I. E. E.

Synopsis.—*This paper is a compilation of many of the new methods for relay protection required by superpower interconnections. The ideas have been obtained from various sources and represent good present day practise. The general requirements for such interconnections are mentioned with particular reference to protection against phase-to-phase short circuits in those cases where the short-circuit current, under certain system conditions, is less than the full-load current under other conditions. The clearing of accidental grounds is discussed and a new study of residual currents on systems of different types is given. This study indicates the usefulness of certain inverse time limit relays on systems having dead grounded power transformer neutrals at all switching stations. Bus protection and "back-up" methods are described.*

Some of the new relays which have been developed, or improvements which have been made to older types in order that the new demands may be met, are described; and there is illustrated a typical relay installation similar to that now being placed in service on a 220-kv. interconnection.

* * * * *

THE interconnection of large power systems requires special treatment of its protective relay installation in order to secure proper automatic sectionalizing. This is particularly true of extra high-voltage interconnections which have their transformer neutrals grounded at all stations. Such systems are not numerous, but they are important and their number is increasing. In any such relay installation it is important to adopt protective methods which not only are suitable for the immediate requirement but which will be applicable to future revisions and extensions. Interconnections between large power units impose more strenuous demands on the relay protective equipment than do individual systems, even those of a large size. The problem is different and in some ways more difficult.

Relay Requirements

The most important requirement is that all faults be cleared quickly. This prevents unnecessary burning of conductors and equipment, but primarily, such quick clearance will minimize the possibility of the system becoming unstable. Therefore the securing of discrimination by means of time limit relays is not desirable although it may sometimes be necessary or convenient.

The complete installation must allow flexibility of system operation. Perfect protection should be possible when any line or piece of equipment is cut out of service and, what is more difficult, protection should be obtained without change in relay adjustment when a large unit of power is entirely removed.

The initial relay installation should permit unlimited extension and revision of the power system.

It should operate satisfactorily on the lines forming the interconnection between the systems without requiring too great a change in the relay protection already installed on the individual systems which are being united.

It must protect against "bus faults." High-voltage switching stations have become so elaborate that the possibility of trouble on the bus bars or on the station equipment is as great as that of a number of miles of transmission lines.

It must provide "back-up" protection; by this is meant that trouble should be cleared from the system, possibly with some little delay, even though the circuit breaker which would ordinarily clear such trouble should fail to operate. Some types of relays will operate in this manner by means of their inherent characteristics, but other types require the use of additional relays. For simplicity it is desirable that protection against bus faults and back-up protection be obtained by the same means, thus making unnecessary the use of complicated differential schemes commonly used for bus protection.

It is desirable to eliminate the use of high-voltage potential transformers so far as possible, not only because of their expense, but also because of the hazard which they, themselves, introduce in the system.

Economy in the relay system is desirable, but because high-voltage lines and equipment are inherently expensive, if such a procedure results in eliminating more expensive high-voltage equipment the best over-all economy may be obtained by adopting an expensive relay system.

Types of Relays Considered. In order to satisfy the needs of recent interconnections, a number of new methods of using the conventional types of relays have been developed and entirely new relays have been designed; namely:

For protection against short circuits,

1. Low-current range impedance relay (type *C Z*).
2. Fault detecting over-current and undervoltage relays.

For protection against grounds,

3. Definite time, directional relay with phase compensation in the potential circuit (type *C R*).

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1. Both of the Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.

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4. Definite time, current directional relay (type *C R C*).
5. Inverse time, current directional relay (type *C W C*).
6. Inverse time, directional relay with phase compensation in the potential circuit. (type C W).

The use of these new methods and devices will be described herein with only brief references to methods which are already in common use.

Protection Against Phase-to-Phase Faults

General Conditions. The nature of a high-voltage interconnection system is such as to make difficult any application of relay equipment which will satisfy the demands previously enumerated. The purpose of an interconnection is usually to permit the exchange of power, and any number of causes may necessitate periodic changes in location of connected generating capacity. These changes may occur daily due to load conditions, or seasonally due to change in available generating capacity. This results in a change in magnitude of fault current, due not only to the variation in total connected generating capacity, but also to the change in location of this capacity. Thus, at some points on the system, it is quite conceivable that fault currents which should cause relay operation may be smaller under some conditions than the maximum load current under other conditions.

The interconnecting system is usually composed of

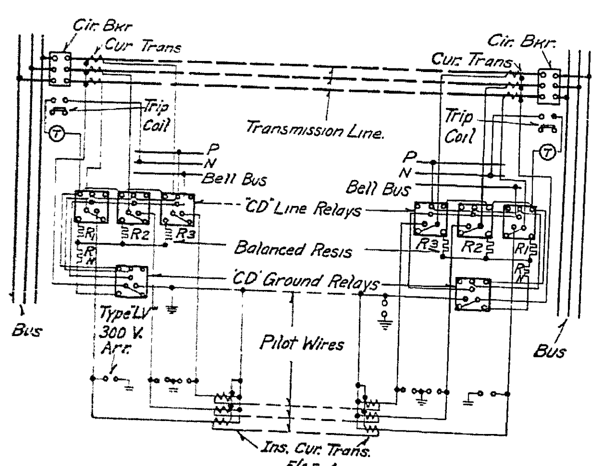


Fig. 1—Balanced-Current Pilot-Wire Scheme Using Selective Differential Relays

long high-voltage transmission lines capable of transmitting relatively large blocks of power. The high load capacity of these lines reduces the number of parallel lines necessary, thus making protection difficult. Also, the expense of substations or switching stations is high and their number is therefore correspondingly reduced. To reduce expense, the system may adopt the form of a triangle, or loop, only one of a pair of lines may be carried through a substation, or different routes may be followed by the various lines.

In addition to these difficulties, later extensions invariably tend to complicate relay protection.

Pilot Wire Protection. To clear faults in the minimum time, theoretically, the best solution probably lies in the use of differential bus protection and pilot wire line protection. Fig. 1 illustrates a pilot wire scheme which has several advantages. This is a circulating current scheme and the burden imposed on the current transformers is quite low. In this method, open circuits on pilot wires put the relay in an operative

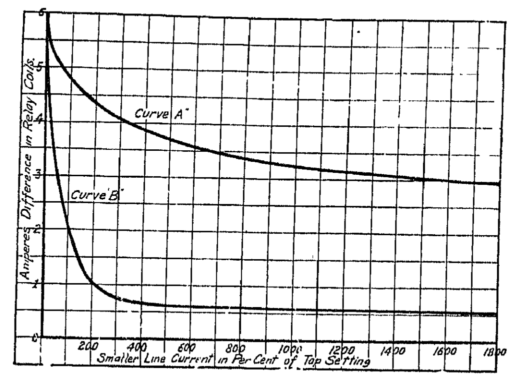


Fig. 2—Tripping-Current Characteristics for Selective Differential Relays

Relay No. 1 Fig. 3 operates on Curve A
Relay No. 2 Fig. 3 operates on Curve B
Relay set on 3-ampere tap

condition for faults either external or internal to the section. This scheme is novel, in that four balancing resistors are used instead of three, with the result that balanced conditions are maintained irrespective of whether a through fault is phase-to-phase or phase-to-ground. This permits the use of ground relays having a low-current setting, thus increasing the sensitivity of the protection. However, for applications where ground fault protection is not desired, the ground relays (but not the balancing resistors, R_n), may be omitted. If the ten-to-one ratio insulating current transformers be used, this protection may be applied to lines of great length because of the effective low impedance of the pilot wires. For shorter lines, where the pilot wire impedance is low, the insulating current transformers may be omitted unless they are required for protection against high voltages. With insulating current transformers of the ratio shown, the balancing resistors R_1, R_2, and R_3 should each be equal to 1/200 of Z, the pilot wire impedance, plus the impedance of the insulating current transformers; but the neutral balancing resistor, R_n, should be equal to 1/200 Z only.

The characteristics of the type *C D* selective differential relay as shown in Fig. 2 are quite suited to this application. Its design is such that, with a fault in a section protected by this pilot wire scheme, the breaker through which the maximum current is flowing will operate on curve *A* and that through which the mini-

mum current is flowing will operate on curve B. As a result, that breaker which has the least tendency to trip is operating on the most sensitive characteristic of the relay.

Although the pilot wire scheme of protection approaches very closely the ideal, the difficulty of installing and maintaining pilot wires prevents its use on all but the shortest transmission lines. The periodic tests, which are essential to all protective equipment, are rather intricate on this scheme. Another objection to this scheme is found in that additional relays must be installed for back-up protection.

Carrier Current Protection. In order to overcome the disadvantages of using pilot wires, effort has been made to use the transmission lines as pilot wires by superimposing on them high-frequency potentials or currents, as is customary for carrier-current telephony. The advantages of this scheme over the pilot wire scheme lies in the fact that no additional wires are necessary. For protecting transmission lines by means of superimposed high frequency there are two general methods which correspond fairly well with the standard pilot wire scheme. In one scheme, radio frequency currents are used, produced by a separate generator at each end of each section of line. The generator is connected to the current transformer on the power line in such a way that the emission of impulses is controlled by the direction and amount of the line current. Reception of the impulses at the other end of the line is controlled by the current transformer at that end and the complete arrangements are such that the radio relays will permit the breakers at each end of a line to be tripped whenever the power current flows into the section from both ends. The actual tripping is done by over-current or directional relays of the conventional type. In order to keep the high-frequency current in its own section of line a tuned reactor is placed between each power conductor and the bus bars.

Another scheme makes use of a lower frequency, say from 500 to 2000 cycles, generated by several small three-phase generators located at various points on the system, the high-frequency potential being superimposed on the main power supply. This superimposed frequency is high enough so that very little of it will leak through the power apparatus because of its high impedance to the high frequency. When a fault occurs, the nearest high-frequency generators cause a heavy current to flow and operate high-frequency over-current relays at each end of the faulty line. The distant relays will not be operated because the impedance of the system to such high frequencies keeps the current down to a small value. In many cases it is necessary to put a small reactance in each end of a section of line in order to make sure that the current in the good sections will be kept small.

Both of the high-frequency schemes have features which appeal to the protection engineer, and it is quite likely that as experience is gained in their operation, they will become popular.

Bus Protection. When either a pilot-wire or a carrier-current scheme is used, some form of bus protection must be applied. Many engineers hesitate about installing differential protection where many bushing-type current transformers must be connected in parallel. Heel-and-toe switches connected in the current transformer leads and operated by the breaker are sometimes used under such conditions, but are generally considered as a hazard and therefore to be avoided if possible.

To overcome these objections and the complex connections of the standard bus differential, protection is often provided against phase-to-ground faults only. One means of doing this is by grounding the tower structure through current transformers. The current transformer secondaries are connected in parallel and operate a relay to clear the bus. It is not necessary that any special precautions be taken to isolate the tower from ground since the relay may be set to operate on only a portion of the total fault current.

This scheme may be amplified so as to isolate portions of the tower structure (electrically) from others, grounding each separately and thus permitting the isolation

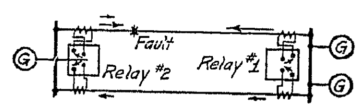


Fig. 3—Single-Line Diagram Showing Current Connections of Selective Differential Relays for Parallel Line Protection

of only the faulty section of the bus. The insulation required between tower sections for this application need be only for low-voltage, or rather in the nature of high resistance.

Parallel Line Protection. The desirable characteristics of the selective differential relay (as shown in Fig. 2), makes it suitable for protection of parallel lines provided there is a source of feed at each end. When the operating currents through the relay coils are in the same direction, as shown in Fig. 3 by relay No 1, the indications are that the fault is near the other end of the line and the relay operates on the least sensitive characteristic, as shown in curve A of Fig. 2. When the currents through the relays are in opposite directions, as indicated by relay No. 2 in Fig. 3, the indications are that the fault is close to that particular relay. This relay then operates on the sensitive characteristic shown in curve B, thus permitting of the relay being installed at stations where only a small amount of feed-back is available. If the relay operation is not simultaneous, the opening of a breaker by one set of relays then permits the other set of relays to operate on the more sensitive characteristic curve.

During conditions of single-line operation, the differential relay is usually inoperative, and some form of

back-up relay is essential. The application of differential relays is therefore usually made in conjunction with back-up over-current or directional over-current relays, the differential relays being inoperative during conditions of single-line operation. The back-up relays also furnish protection against bus faults. Therefore, balanced protection on parallel feeders approaches the protection afforded by pilot wires during conditions of parallel operation, but for faults within the section during single-line operating conditions a long time is required for clearing, since selective settings are then used.

Under many operating conditions, a substation may

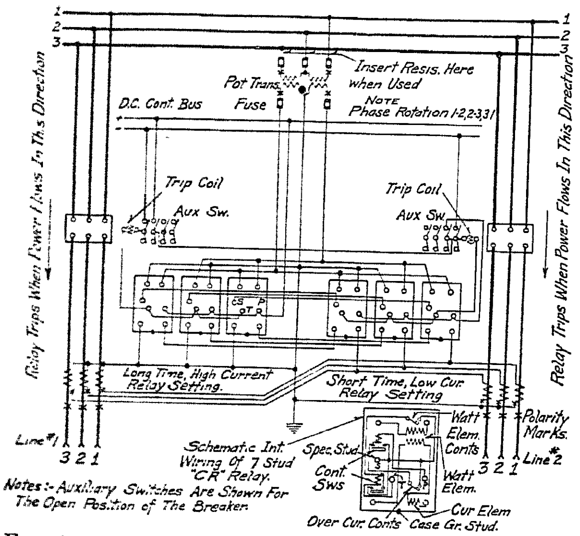


FIG. 4A—PROTECTION FOR A PAIR OF PARALLEL LINES

Effective for both parallel and single-line operation, using directional over-current relays

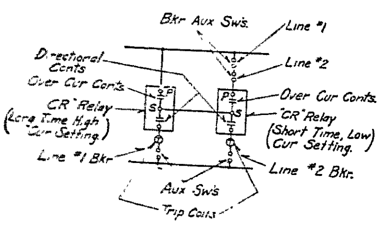


FIG. 4B—SCHEMATIC DIAGRAM OF TRIP CIRCUITS OF FIG. 4A

have a connected source of feed-back into a fault, so that directional back-up protection is necessary during conditions of single-line operation. For this application, cross-connected, over-current, directional relays are applicable. This scheme is shown in Fig. 4A. The relays each consist of a directional element and an over-current element, the contacts of the two elements being connected in series. The common points of these two sets of contacts is brought out of the relay case by a separate stud. The directional elements in both sets are practically instantaneous. The over-current element in one set of relays is given a short-time, low-current setting, and the over-current element in the other set is given a long-time, high-current setting.

Fig. 4B shows the schematic diagram of the trip circuits. The common studs on the two sets of relays are tied together for each individual phase so that, from this common connection, each directional element may trip its individual breaker. During conditions of parallel-line operation, the closing of either set of over-current contacts will cause the tripping of one or the other breaker, depending upon which directional element is closed. The disconnection of one line or the other, producing the conditions of single-line operation, causes the low-current short-time over-current elements to be disconnected from the circuit so that tripping must be performed by the relay having the high-time setting. These high-time over-current relays are set so as not to operate under conditions of maximum load current, and also to give the proper selective setting.

The objections to the use of balanced protection lie in the fact that the relays which give quick clearing of faults afford no back-up or bus protection, and extra relays must be used for this purpose. Also, under conditions of single-line operation, long-time is required for clearing a fault on the line remaining in service. The cross-connections are relatively complicated, and testing and checking is made more difficult. In addition to these objections, the cross-connected directional relay protective scheme requires a source of potential. This objection, however, is not serious, since a suitable low-voltage set of potential transformer is nearly always available and the secondary potentials from these potential transformers may be used.

Impedance Relays. The application of impedance relays satisfies many of the demands placed on protective equipment for interconnections. Particularly is it true that rendering the system more complex does not necessitate increased time for operation, nor does the relay place limitations on the permissible system connections. The time required for clearing faults does not become cumulative. Bus protection, quick clearing of faults, and single-line protection are all secured.

Used on transmission lines, irrespective of whether parallel lines or single lines are in service, the impedance relay will clear faults as quickly as will balanced relays, when faults are located near the extremities of the line. With a fault in the center of the section, the impedance relays will clear in approximately four-tenths of a second; and balanced relays, under the best operating conditions, may clear these faults faster than will the impedance relay. On the other hand, the impedance relay operates effectively irrespective of whether one or two lines are connected in parallel and is independent of other changes in operating conditions.

Fig. 5 shows a typical connection of impedance relays. When applied in this manner, the relays protect against

phase-to-phase faults only and constitute only a small measure of protection against phase-to-ground faults. The use of potential is required with the impedance relay, but this objection may be overcome, as previously mentioned, by using low-voltage potential transformers. Another method of obtaining correct potential for relays when high-voltage potential transformers are not available is covered later.

Relay Operation with Low Current Faults. To meet fully the requirements of relay equipment applicable to

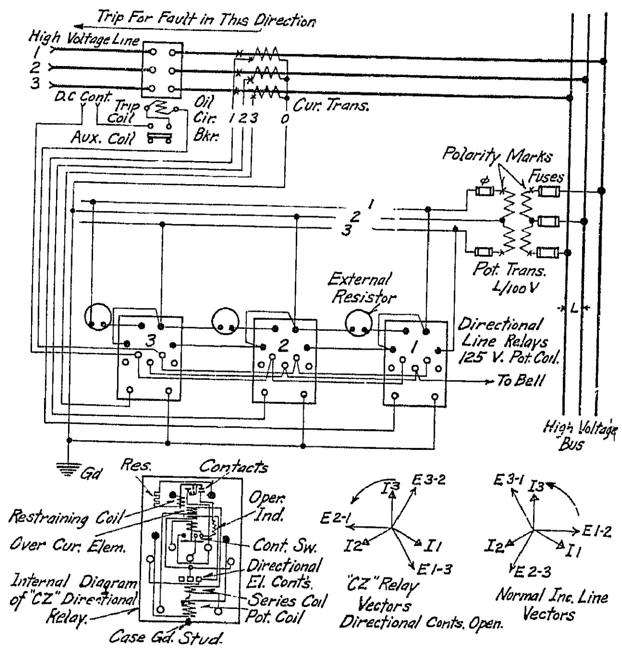


Fig. 5—Typical Connection Diagram of Impedance Relays Applied to Sectionalize Wire-to-Wire Faults on Transmission Sections

interconnections, the relays must operate on fault currents, which may be less than full load current. In order to satisfy this demand, a fault-detecting device has been developed,—a device composed of an under-voltage and an over-current element connected in each phase. The contacts of these elements (two per phase or a total of six) are connected in parallel, so that any conditions of either undervoltage or over-current will cause the relay contacts to be closed. In applying this device, the over-current element is set to operate at a current value corresponding to approximately 125 per cent of the maximum load which is expected in practise. Therefore, the current relays should never operate unless heavy fault currents are flowing. The under-voltage device is set for, say, 75 per cent of normal voltage.

The principle of operation of this combination is quite simple. If the distribution of generating capacity is such that the bus voltage will not drop below approximately 75 per cent of normal, the current to a fault near the bus must necessarily be high. On the other hand, if the magnitude and distribution of the generating capacity is such as to permit only a small current to flow to the fault, the bus voltages near this fault must necessarily be very low. As a result, either the over-current or the undervoltage relay is sure to operate with a fault so located as to demand their operation for proper clearing. In order to fully meet the various conditions existing in practise, both the over-current and the undervoltage relays have a suitable range of adjustment.

These relays are used in conjunction with standard low current relays in such a manner as to render the protective relays inoperative until a fault occurs. The fault detector relays may be used in conjunction with directional relays connected as shown in Fig. 4A to guard against the following two conditions, which are likely to cause faulty operation on interconnections.

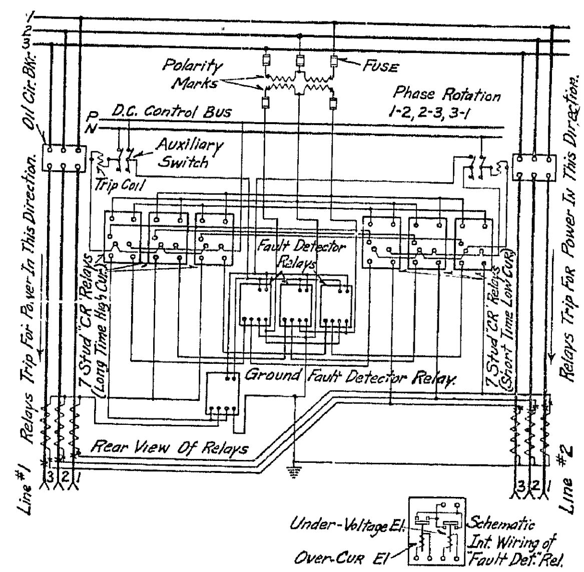


Fig. 6A—Protective Scheme for a Pair of Parallel Lines when Fault Current May be Less Than Load Currents

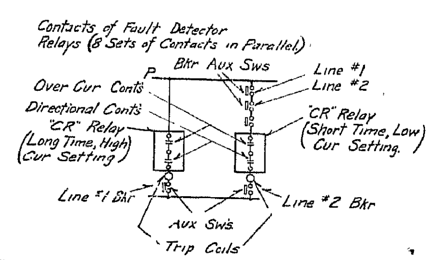


Fig. 6B—Schematic Diagram of Trip Circuits of Fig. 6A

The first of these conditions occurs only when the low-set relays have current settings for less than full load. The faulty operation is caused when an operator at a receiving substation trips one of the breakers on a pair of parallel lines carrying nearly full-load current. This causes all current to flow over one line and this line will be tripped at the sending end by the low-set relays. To correct this trouble, fault detector devices may be applied as shown in Fig. 6. As shown in the schematic diagram, Fig. 6B, the contacts of fault detec-

tor relays are so connected as not to permit the low-setting over-current contacts to cause tripping unless a fault occurs on the system. The low-setting relays may therefore be given a current setting of any value without danger of tripping due to this operating condition.

The second condition occurs when it is necessary to set both the short-time and long-time relays to operate under less than full-load conditions. The connections are then changed so that the current elements of both the long-time and short-time directional relays are

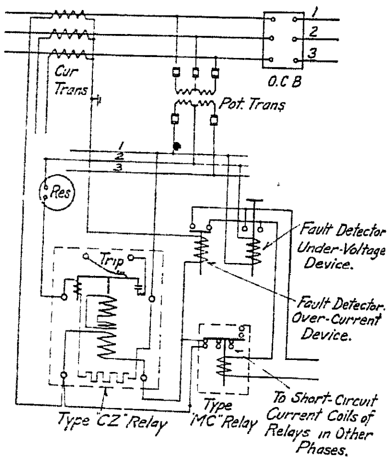


Fig. 7—Application of Impedance Relays for Protecting Systems where Fault Current is Less than Full-Load Current

normally short-circuited by back contacts of an auxiliary relay. This relay has three back contacts (each one short-circuiting the directional relay's current coils in one phase), and a front contact to be used for connecting in the tripping contact circuits, or for bell alarm, as may prove desirable. This auxiliary relay is normally deenergized and is energized when any of the fault detector relays close contacts due to fault conditions. When this connection is used, the relays may be given a sensitive setting without danger of tripping out due to heavy load conditions, since the short circuit is removed from around the current coils only under fault conditions.

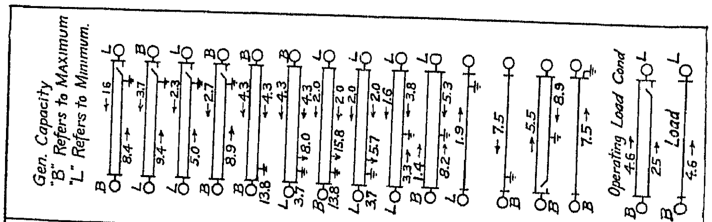
Fig. 7 shows another application of the fault detecting relay. In this application, operation of the line protective relay under heavy load conditions is again prevented because the current coils of the relay are short-circuited. The fault detecting relays, when deenergized, permit the back contacts of the auxiliary relay to short-circuit the line relays. The fault conditions on the system cause the contacts of one or more elements of the fault detector relays to close, thus energizing the auxiliary relay and removing the short circuit from the impedance relay. Then the impedance relay is permitted to function, and will operate, if the impedance between the station bus and the fault is sufficiently low.

Thus, after a fault on the system has occurred, all impedance relays on the system are connected into service, permitting the one nearest the fault to open the circuit breakers on the faulty section. Since the impedance relay current coils are normally short-circuited, they may be set on the one-ampere tap although maximum load currents may be five amperes. This scheme has a second advantage, in that the relay burden is removed from the current transformers except under fault conditions.

Fig. 8 illustrates an actual analysis which was made on a pair of parallel lines constituting a portion of a complicated interconnecting system. The single-line diagrams illustrate various operating conditions with maximum and minimum connected generator capacity, and with faults at various locations. A study of this indicates that the maximum load possible on the system is 4.6 amperes, and the minimum short-circuit current is 1.9 amperes. The figures given refer to secondary amperes. This analysis indicates that, of the schemes considered, the one- to six-ampere impedance relays, in conjunction with fault detector relays, provide the most satisfactory protection.

Phase-to-Ground Fault Protection

Advantages of Ground Relays. The advantages resulting from application of ground relays for pro-



CD 3 Amp. Tap	O.K.	O.K.	?	O.K.	O.K	O.K	O.K.	?	?	O.K.	—	—	—	—	O.K.	—
CD As O.L.	O.K.	O.K.	?	O.K.	O.K.	O.K.	O.K	?	?	O.K.	X	O.K.	O.K.	?	O.K	O.K.
CD 1.5 Amp. Tap	O.K.	O.K	O.K.	O.K.	O.K	O.K.	O.K.	O.K.	O.K.	O.K.	—	—	—	—	X	—
CO 6 Amp. Long Time	O.K.	O.K.	X	O.K	O.K.	O.K.	O.K.	X	X	O.K	X	O.K.	O.K.	?	O.K.	O.K.
CZ Line 4 Amp.	O.K.	O.K	?	O.K.	O.K.	O.K	O.K.	?	X	O.K	X	O.K.	O.K	O.K	O.K.	O.K.
CZ Line 5 Amp	O.K	O.K	X	O.K.	O.K	O.K	O.K.	X	X	O.K.	X	O.K.	O.K.	O.K.	O.K.	O.K
CZ Trans. Bank Long Time	X	O.K	X	X	O.K	O.K	O.K.	X	X	X	?	O.K.	O.K.	O.K.	O.K.	O.K
CR Cross Connection	O.K.	O.K	O.K.	O.K	O.K	O.K.	O.K.	O.K.	O.K.	O.K	X	O.K.	O.K.	?	X	O.K.
CZ Line 1 Amp	O.K.	O.K.	O.K.	O.K.	O.K	O.K	O.K.	O.K.	O.K.	O.K.	O.K.	O.K.	O.K.	O.K.	O.K.	O.K.

? Relay Operation Doubtful.
X Relays Can not Operate Because of Low Current Fault.
— Relays Can not Operate Because of Open Pallet Switches.

Fig. 8—Comparison of Relay Schemes for Protection of a Pair of 220-Kv. Transmission Lines

tection of transmission circuits are now well established. These advantages may be briefly itemized as follows:

a. Ground relays operate on residual currents and so may be given a more sensitive setting than can the relays protecting against line-to-line faults.

b. These sensitive settings are necessary because the magnitude of ground currents may be reduced below that value necessary to cause prompt operation of the relays normally protecting against line-to-line faults either by impedance in the neutral connections of the

transformer banks by resistance at the point of fault or by the high earth return impedance.

c. A high percentage of faults on transmission line cause ground current to flow. Thus, the residual relay, with its relatively quick timing, increases the speed of clearing a large percentage of the faults.

d. When this relay is used, those protecting against phase-to-phase faults act as a back-up protection.

e. On certain types of system connections, an inverse-time, over-current, residual-current relay may be used and the distribution of ground current is such as to cause the relays closest to the fault to operate always very quickly.

Distribution of Residual Currents. On a system where the neutrals of all equipments are solidly grounded, the distribution and magnitude of fault currents differ depending on the type of faults. As a result of this, the study of phase-to-phase fault conditions may not be sufficient to permit accurate setting of relays used for protection against phase-to-ground faults. In many cases a special study is required to determine the distribution of ground current, and this study quite frequently shows that protective equipment which is superior to that available for phase-to-phase fault may be applied for protection against phase-to-ground faults.

The Method of Symmetrical Components (phase sequence) for analyzing fault conditions on transmission lines, developed by C. L. Fortescue,[2] simplifies this otherwise complicated problem. The magnitude of residual currents may be determined with little more effort than that required for the determination of the positive phase sequence quantities corresponding to a three-phase fault. To show the desirability of making this separate study, and to illustrate applica-

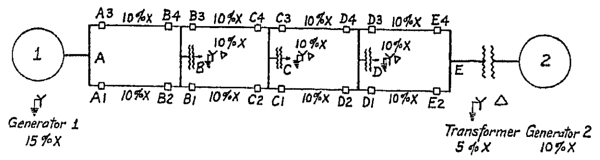


FIG. 9—SYSTEM LAYOUT FOR ILLUSTRATING CURRENT DISTRIBUTION

tion of ground relays, a few results of a study of a simple system are given.

The system used in these calculations is shown in Fig. 9. At one end of the system a generator is shown connected through a transformer bank, and at the other end of the system a generator is connected directly to the system. This has been done to illustrate that some difference exists depending on whether the generator is connected directly to the system or through a transformer bank. The reactance of both the generator alone, and of the generator in combination feeding through the transformer bank has a total impedance of 15 per cent.

The transformer banks at the substations are in some cases assumed to be connected star-delta with solidly grounded neutrals, so that they have the effect of grounding transformer banks on the system. To illustrate the effect of these banks as compared to delta-connected banks, certain calculations have also been made with the transformer banks disconnected from the substation busses.

Fig. 10 illustrates the distribution of conductor cur-

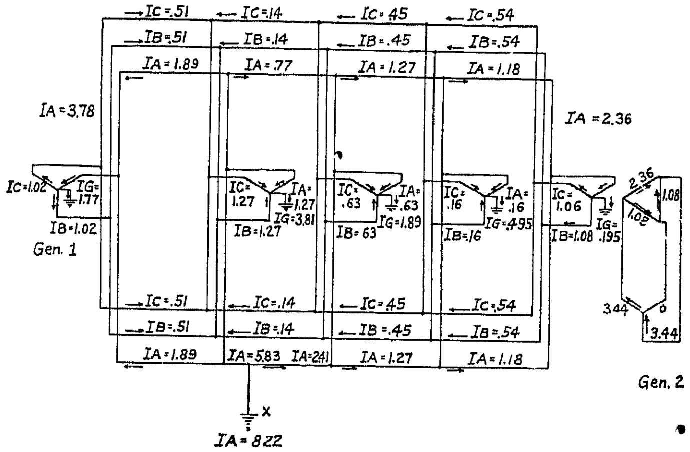


FIG. 10—FAULT-CURRENT DISTRIBUTION DIAGRAM

Showing effect of grounding the neutral of substation power banks

rents throughout the system with a fault located between Stations B and C on phase A conductor of one of these parallel lines. Fig. 11 illustrates the distribution of conductor currents for a similar fault; but here, the substation transformer banks are assumed to be delta-delta connected. I_A, I_B, and I_C are the phase currents and those marked I_G are the generator and transformer bank neutral currents.

By comparing these two figures, it will be seen that the magnitude and distribution of conductor current is radically changed, depending upon whether the substation transformer bank neutrals are solidly grounded or not. In Fig. 10 the biggest portion of the ground current flows through the neutrals of the substation transformer banks adjacent to the fault. The banks farthest from the fault pass only a small amount of residual current, the magnitude decreasing as the distance to the fault increases. This residual current distribution will vary depending upon the relative impedances of the transformer banks and transmission lines to the flow of zero phase sequence current, and therefore demands special study.

Fig. 12 illustrates the difference in current distribution, depending on the type of faults and type of system. Fig. 12A shows the distribution of current for a three-phase fault. Fig. 12B illustrates the distribution of residual current for a fault located as shown on Fig. 10. The values shown in Fig. 12B are equal to

2. A. I. E. E. TRANS., 1918, Vol. XXXVII, Part 2, p. 1027.

three times the zero-phase sequence current. They are therefore the residual currents which would flow through the relay coils of the ground relays. It is to be noted that here the current in the relays on the faulty section is much greater than that in any other relays on the system. This is true irrespective of whether the lines are connected in parallel or whether one line is disconnected from service. Fig. 12C illustrates the residual current which would flow through the ground relay coils for a fault located as shown on Fig. 11.

Figs. 12A and 12C resemble each other very closely, the only difference being due to the increased reactance of the transmission line for phase-to-ground fault conditions over the reactance for a three-phase fault. As a result, on systems corresponding to Fig. 12C, the same system of relaying has been generally used for protection against phase-to-ground faults as is used for protection against phase-to-phase faults. The greatest

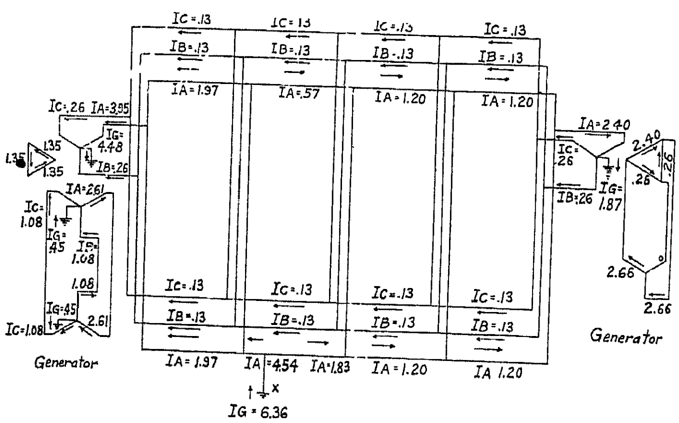


FIG. 11—FAULT-CURRENT DISTRIBUTION DIAGRAM

Conditions identical with those shown in Fig. 10 except that substation transformers have been removed. Generator No. 1 has been replaced by an equivalent impedance

advantage of ground relays may be obtained from the current distribution as shown in Fig. 12B. Here, definite advantages in selectivity, speed of clearing, and sensitivity may be obtained by the use of ground relays. A comparison of Figs. 12A and 12B will illustrate that the use of ground relays with proper characteristics would assist materially in securing suitable relay protection on a system of this type.

Definite-Time Ground Relays. Fig. 13 shows a diagram of connections for relays suited to the protection of a system with current distribution similar to that shown in Fig. 12B. This diagram shows selective relays applied as for protection against single-line operation. Standard directional relays are used for protection against phase-to-phase faults. The directional ground relay is of the low energy type with low-current setting. It also differs from the directional relays used for protection against phase-to-phase faults, in that maximum torque is obtained on the directional element of the ground relay when the relay current lags behind the relay potential.

Fig. 14 shows the distribution of residual currents in the system as shown in Fig. 11, except that a fault impedance of 10 per cent resistance is present. The vector diagrams at the various substation busses and at the faults are shown. As may be seen from this,

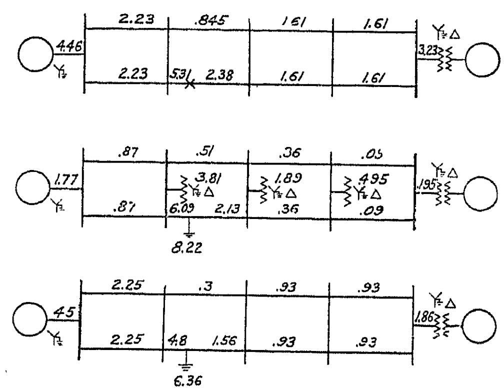


FIG. 12—A COMPARISON OF FAULT-CURRENT DISTRIBUTION WITH IDENTICAL FAULT LOCATION

A—Three-phase fault-current distribution
B—Residual-current distribution with grounding transformers on a line-to-ground fault
C—Residual-current distribution without transformer banks on a line-to-ground fault

the phase displacement between the residual voltage and the residual current on this system will always be 90 deg. so long as the system impedance is pure reactance.

If this were true for all systems, the theoretically

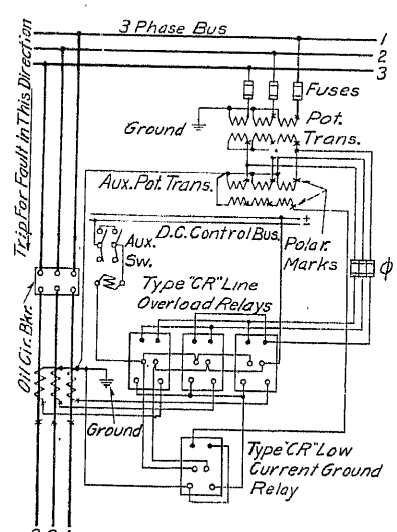


FIG. 13—DIRECTIONAL LINE AND GROUND PROTECTION FOR ONE THREE-PHASE LINE

correct relay to use would be one in which the maximum torque is obtained when there is a phase displacement of 90 deg. between voltage and current. On the actual system, resistance is present in the transmission lines and equipment. This will tend to decrease the dis-

placement angle. Under conditions where the phase-to-ground fault has no resistance and the neutrals of the transformer banks or generators are grounded through a high resistance, it is theoretically possible for the residual current and the residual voltage to be in phase, so that the unity power factor condition should cause the maximum torque. It is therefore desirable

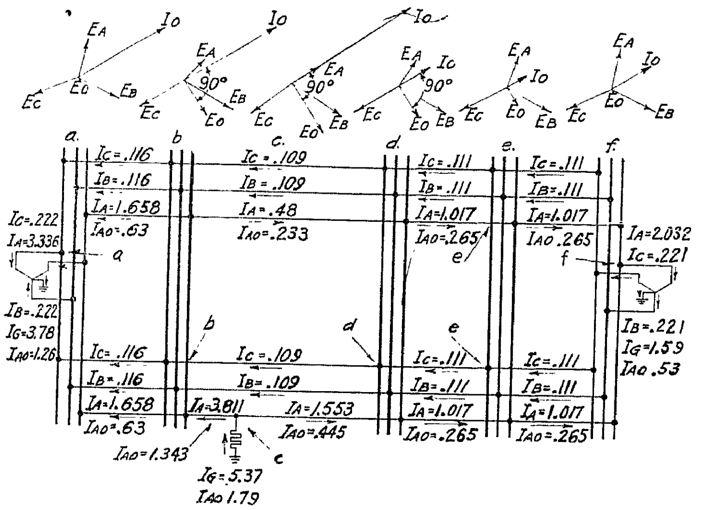


FIG. 14—CURRENT DISTRIBUTION AND VECTOR RELATIONS EXISTING WITHIN RELAYS

For system as shown in Fig. 11 and with a 10 per cent fault resistance

that this type of relay should secure the maximum torque at some angle lying in between zero and 90 deg. so as to be applicable to any system conditions. Until recently, relays commonly used for this purpose have had approximately true watt characteristics, and it

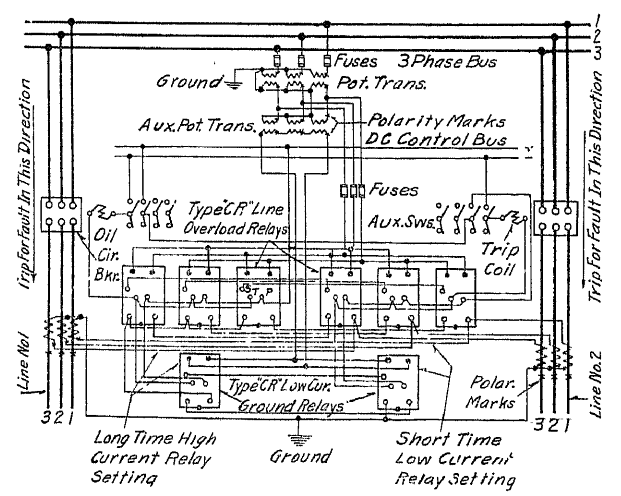


FIG. 15—LINE AND GROUND PROTECTION FOR BOTH PARALLEL- AND SINGLE-LINE OPERATION USING DIRECTIONAL OVER-CURRENT RELAYS

was possible for these relays to operate improperly under certain fault conditions. Where such a relay is now in use, it may be desirable to insert a phase shifting device in its potential circuit so as to obtain the proper phase relation.

The diagram shown in Fig. 15 is more desirable for the conditions shown in Fig. 12C. This diagram is similar to that shown in Fig. 4A, except that the ground relays are included.

In order to avoid using high-voltage potential transformers, the connections shown in Fig. 16 may be employed. As illustrated by Figs. 10 and 12B, the current flowing through the fault is largely supplied through the neutral of the transformer bank nearest the fault. Thus, instead of using a potential as shown

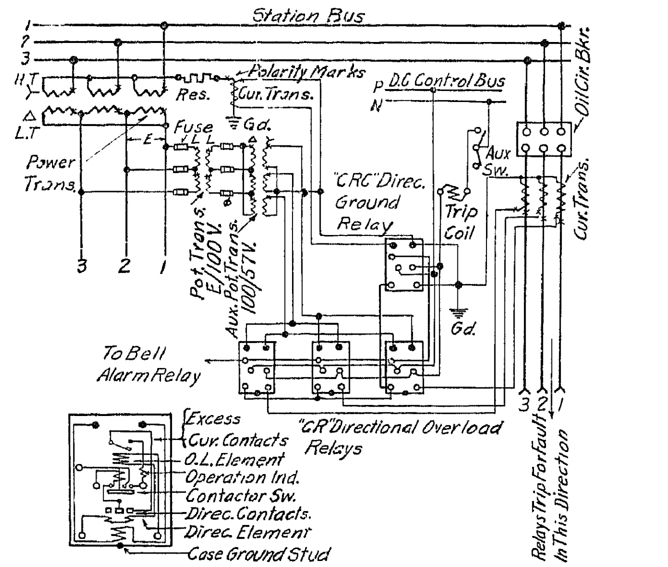


FIG. 16—DIRECTIONAL OVER-LOAD AND DIRECTIONAL GROUND PROTECTION

Using definite time, residual, over-current relays and low-tension potential transformers

Rear view "CRC" directional ground relay is shown in lower left-hand corner

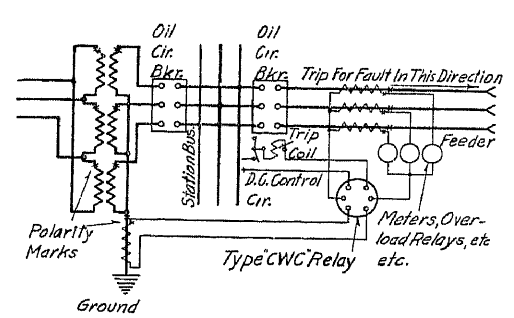


FIG. 17—TYPICAL DIAGRAM OF CONNECTIONS FOR GROUND PROTECTION USING THE INVERSE TIME, RESIDUAL, OVER-CURRENT, GROUND RELAY

in Fig. 13, the neutral current from the power banks may be used to determine the relative direction of current flow in a line. The currents in the line and in the neutral of the transformer bank are approximately in phase, so that the relay should be so designed as to have the maximum torque when the currents in the residual circuit of the current transformers and in the neutral connection of the power banks are in phase. The connections shown in either Fig. 13 or Fig. 16 are

equally good in determining the location of the fault.

Inverse-Time Ground Relays. The diagram shown in Fig. 17 is an alternative for, and under certain conditions, an improvement over that shown in Fig. 16. This scheme was first devised and put into service by Mr. Roy Wilkins.[3] The residual relays used here are inherently directional and in addition, operate with an inverse characteristic that is quite suitable for

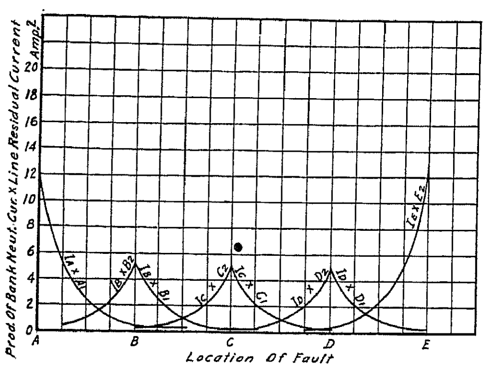


FIG. 18—PRODUCT OF TRANSFORMER BANK NEUTRAL CURRENTS AND RESIDUAL LINE CURRENTS

For any fault location and for phase-to-ground faults for the system shown on Fig. 9

systems where the neutrals of all transformer banks are solidly grounded, as illustrated in Fig. 12B. Fig. 18 shows the operating torque on the relays for the system as shown in Fig. 10. The curves plotted in Fig. 18 are the products of the current in the transformer bank

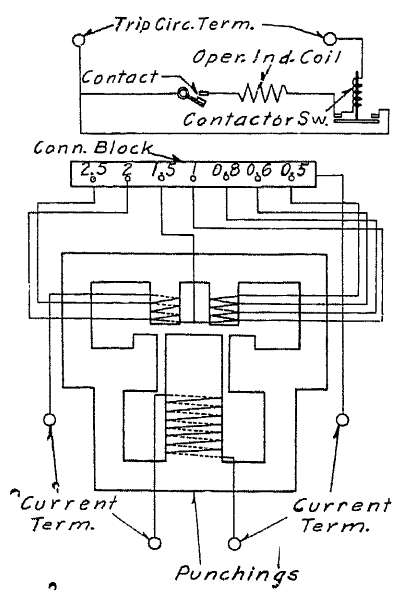


FIG. 19—DIAGRAM OF INTERNAL CONNECTION FOR RESIDUAL CURRENT AND RESIDUAL VOLT-AMPERE RELAYS

times the current in the line at any point on the system. This is the product which would tend to operate the residual current relay when connected as shown in Fig. 17. The operating tendency of the relay decreases rapidly as the fault approaches the adjacent substation bus, so that the quickest acting relay is that which is closest to the fault. In this respect, the relay has the characteristic of the impedance relay. After the breaker closest to the fault has cleared, the current through the relay on the far end of the faulty section increases and causes increased operating torque.

By actual calculations, it may be shown that the relay operating connected according to Fig. 17 will not have quite so selective a characteristic under all conditions as would the device connected as a straight over-current relay as shown in Fig. 21. In some cases, the directional feature is necessary and is obtained as shown in Fig. 17. In many cases, however, the simpler connections shown in Fig. 21 should suffice.

Since an inverse time over-current relay has suitable characteristics, it is logical that an instantaneous over-current device may be used with it to bring the time element down to zero for very heavy currents. Such a relay should be set to operate at a current value

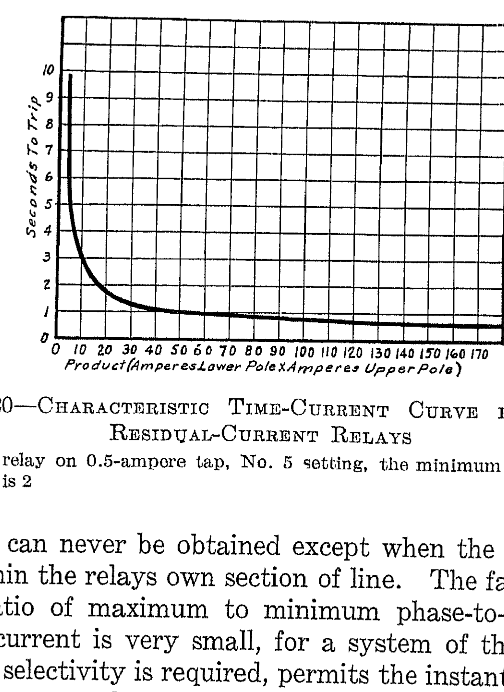


FIG. 20—CHARACTERISTIC TIME-CURRENT CURVE FOR THE RESIDUAL-CURRENT RELAYS

With relay on 0.5-ampere tap, No. 5 setting, the minimum operating product is 2

which can never be obtained except when the trouble is within the relays own section of line. The fact that the ratio of maximum to minimum phase-to-ground fault current is very small, for a system of this type where selectivity is required, permits the instantaneous over-current relay to be effective over a very large portion of the transmission line. Thus, with a fault in the mid-section, in many cases instantaneous operation of the relays will occur at both ends of the section. After one end of the section had been opened, due to either the instantaneous device or the inverse time relay, the current through the other end increases, increasing the likelihood of the operation of the instantaneous device at the far end.

The diagram of internal connections of an inverse-time-directional current relay is shown in Fig. 19. Working on the watthour meter principle, it is quite evident from this diagram that the relay connected as shown in Fig. 17 would be directional. The characteristic curve for this relay is shown in Fig. 20.

3. *Electrical World*, November 22, 1924, p. 1101.

As previously mentioned, the inverse time relay may be used as a simple residual over-current device. Thus, at a switching station similar to that shown in Fig. 21, where neither a low-voltage nor a high-voltage potential transformer source is available, the ground relay may be applied and used as an inverse time over-current

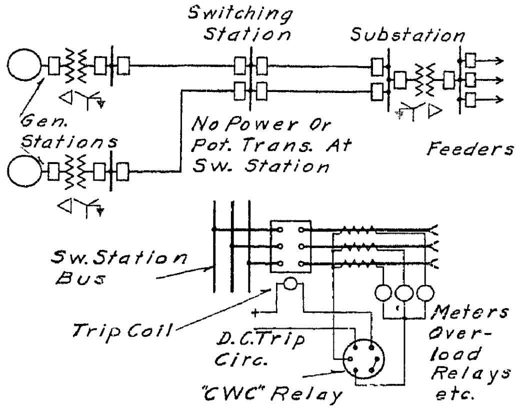


FIG. 21—APPLICATION OF THE RESIDUAL-CURRENT RELAY TO A SWITCHING STATION WITHOUT A SOURCE OF SECONDARY POTENTIAL

device. The relay may be so set that proper selectivity may be obtained at this point so long as three breakers are closed. If only two breakers are closed, in case of any fault, the tie will be dropped and it makes no difference which relays operate.

A modification of the connections shown in Fig. 17 is

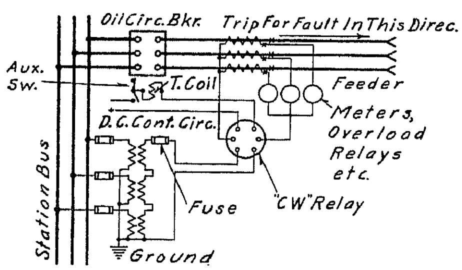


FIG. 22—TYPICAL DIAGRAM OF CONNECTIONS FOR THE RESIDUAL VOLT-AMPERE RELAY

that shown in Fig. 22. Here, a volt-ampere relay is used, the internal connections of which are similar to those shown in Fig. 19. The relay depends upon the principle that the product of the residual current and the residual voltage is greatest when the fault is close to the relay, with the result that the relay closest to the fault operates fastest. In addition to this, the relay is directional.

On a system as shown in Fig. 12C, the residual voltage, or three times the zero phase sequence voltage, increases from each end of the transmission line to the fault. The vector diagrams given in Fig. 14 illustrate the largest product closest to the fault.

The operating forces on this relay would be as shown in Fig. 23 and would apply to the system shown in Fig. 9. Quite clearly, the relay closest to the fault would operate much faster than any other relay on the system. This is true if the relay is so designed that the torque is proportional to the product of zero phase sequence currents and potentials as mentioned above in the discussion of the phase relations in the directional relay in connection with Fig. 14.

This volt-ampere product may be obtained quite accurately by an approximation. The unbalanced voltage, or zero phase sequence voltage which is used on the relay, is usually due to the drop through trans-

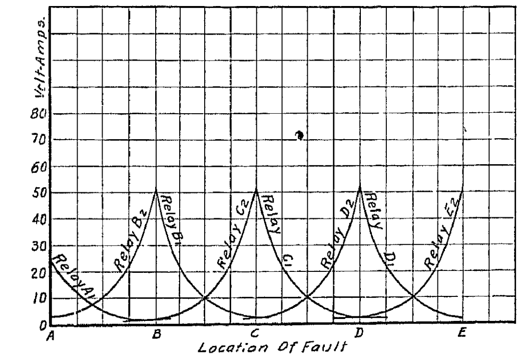


FIG. 23—PRODUCT OF ZERO PHASE SEQUENCE VOLTAGES AND ZERO PHASE SEQUENCE CURRENTS

For various phase-to-ground fault locations on system shown on Fig. 9

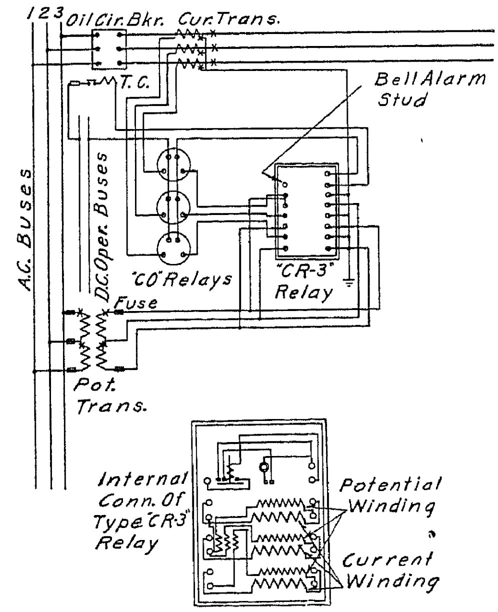


FIG. 24—DIAGRAM OF CONNECTIONS FOR OVER-CURRENT PROTECTION USING A THREE-PHASE DIRECTIONAL RELAY

former banks plus transmission lines up to the relay. The phase angle between this voltage and the residual current may be as much as 80 deg. Taking this as the maximum, one may set the relay so as to secure the maximum torque when the phase displacement is 55 deg. The conditions of the system may then change so that

the phase displacement varies from 80 deg. (0.174 power factor) to 30 deg. (0.867 power factor) without introducing a volt-ampere error of more than 10 per cent. Due to the inverse characteristic of the relay, this small error should cause not more than 5 per cent error in relay time; and this is permissible since approximately the same error is applied to all relays. Therefore 55 deg. is standard, but this should be modified for special cases such as are met when high resistance is inserted on all neutral connections.

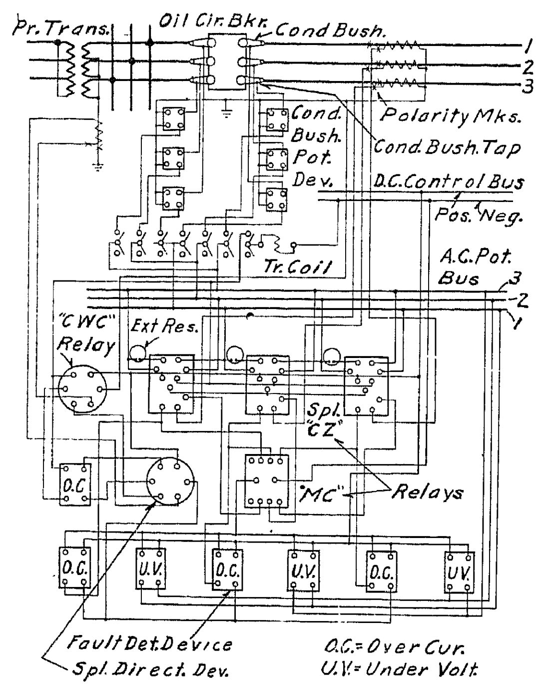


Fig. 25a—Diagram Showing Connections for a Complete Relay Scheme Applicable to a Complex Interconnecting System

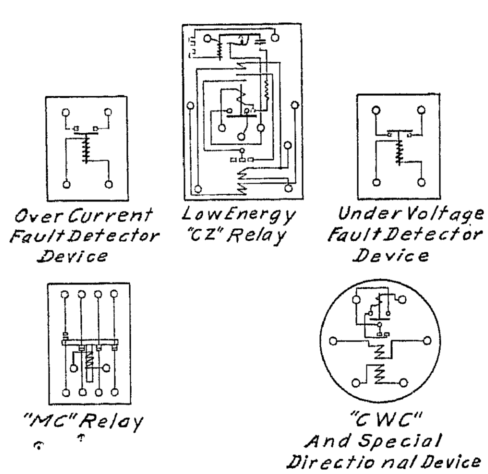


Fig. 25b—Internal Wiring Diagrams

The application of this relay need not be restricted to systems where the neutrals of all power banks are solidly grounded. Since the zero phase sequence voltage on practically any system will be largest on those relays closest to the fault, it can be used in preference to the definite time relays and gain some improvement of timing over them. The objection to this application lies in the difficulty in making the correct setting.

The Use of the Polyphase Directional Relay. The distribution of current on systems with a multiplicity of grounded neutrals, as shown on Fig. 10, is often inimical to correct operation of single-phase directional relays. Heavy currents often flow in all three phases during phase-to-ground fault conditions, with the result that certain single-phase relays may cause the clearing of breakers which should not open. This is particularly true of those systems where ground relays are not applied. Where difficulty is experienced in this particular application, the three-phase relay offers the best solution The connections for a relay of this type are shown in Fig. 24.

In the three-phase relay, the residual current causes a predominating torque during phase-to-ground fault conditions so that the currents in the good phases cannot cause faulty operation. Similarly the fault currents on such a system are always sufficiently large so that the load current will never affect the relay in such a direction as to prevent proper operation.

A Typical Relay Installation

Fig. 25 represents a composite picture of relays suitable for application to a system as shown in Fig. 9. Impedance relays are used for protection against phase-to-phase faults, so that the maximum time of relay operation is three-quarters of a second. The average time will be much less than that and will approach very closely the timing obtained by parallel-line protection.

Potential for these devices may be obtained from low-voltage potential transformers with suitable compensators, from high-voltage potential transformers, or from a tap on the condenser bushing of the circuit breaker. The voltage thus obtained is higher than desirable, and must be reduced and its phase shifted by means of a small stepdown transformer and network, according to a method developed by J. F. Peters.

The load conditions on the system here shown are assumed to be such that fault currents of less than full-load magnitude must be guarded against. For this reason, low-current setting impedance relays are used and these relays are normally short-circuited by the auxiliary relay contacts. The fault detector relays operate under conditions of either over-current or under-voltage to remove this short circuit from the impedance relay coils. The residual relay is used to obtain the selective timing necessary for protection against phase-to-ground fault. In addition to the inverse time residual relay, an instantaneous over-current relay has been added to increase the speed of operation over that afforded by the residual relay for certain fault conditions. For this particular application, a directional

instantaneous over-current relay was necessary and the directional element has therefore been included in a separate case.

This protective scheme compares very favorably with the ideal system for interconnections as previously specified. It has the following advantages:

1. The quick clearing of faults.
2. System operating set-up does not affect relay operation.
3. Relay system permits unlimited system extensions and revisions without necessitating increased relay timing.
4. The relay system should necessitate little or no change on the installed relay equipment protecting the individual systems combined by the interconnection.
5. Relays afford protection against bus faults.
6. Back-up protection against faulty operation of relays or breakers is afforded by this system of protection.
7. High-voltage potential transformers are not required. The breaker equipped with bushing type current transformers supplies both current and potential for the relays. Potential may also be obtained from low-voltage potential transformers.
8. The relay equipment is simple, standard, and economical.

Discussion

H. D. Bradley: It might be well to point out in connection with the potential and ground relay, as mentioned, that there is a possibility of improper operation unless the potential transformers are single-phase. I refer to the scheme in which the star-delta-connected potential transfers were used, with the neutral of the star side grounded.

We had some experience along that line on lower voltage systems using three-phase potential transformers and learned that when a ground occurred on the system the fuses were blown and the relays were rendered inoperative, or operated incorrectly. The ground phase of the transmission line put a short circuit on one phase of the potential transformer, and due to the coupling of the magnetic circuits it virtually placed a short circuit on the potential transformer and resulted in blowing the fuses on the other phase. It is also possible in some cases to get the improper operation on the potential in directional relays.

We are getting away from that sort of operation by putting on a lock-out device similar to that described in the author's paper.

In the New York system we have a source of back feed to the 132-kv. cable which permits us to use a directional ground relay. This, we think, can be set to operate to pick up on less than 100 amperes.

E. E. George: (by letter) Perhaps the only statement that might be questioned by some is that referring to the hazard of high-voltage potential transformers. High-tension bushings are used on switches and power transformers with so little trouble that the question of their hazard probably does not prevent their wider use.

The balanced pilot-wire scheme in Fig. 1 looks very good for short lines.

It is to be hoped that we will soon get abundant operating experience from the industry on the use of carrier-current pilot protection, especially on intercompany tie lines.

There is a demand for a relay which will open tie lines when an out-of-step condition prevails.

The scheme (shown in Fig. 21) of using a directional ground relay as a straight ground relay to get the same timing characteristics is very ingenious and should be applicable in many locations.

It is possible to use the scheme shown in Fig. 17 with a very small grounding transformer. In fact we have one installation where the grounding transformer cost less than three potential transformers would have. Since the phase angle is so small between the ground current in the grounding bank and the ground current in a faulty line, there is little opportunity for this relay to work incorrectly on account of variations in power factor. Such variations are a liability of the type of ground relay shown in Fig. 16.

It is very encouraging to see the discussion of the advantages of ground relays. Operating experience seems to bear out all of the advantages claimed.

In enumerating the advantages of ground-relay protection, perhaps some mention should be made of the necessity of providing good bushing current transformers and of the advisability of testing them with current in one phase only after all connections have been completed, so as to get the full by-passing effect of the two phases which are not energized, as well as of the high impedance in the neutral circuit which does not apply for phase-to-phase faults. These difficulties are being overcome by the use of better iron in bushing current transformers, the use of larger current transformers containing more iron, and by the use of two current transformers in series per phase, which is standard practise with several companies. Ground tests at full system voltage provide the best over-all check of relay type, setting, and connection.

The diagram shown in Fig. 2 is very interesting, but a little more explanation might be desirable. For instance, it should be made clear whether this type of relay has the same time characteristics with the currents in the two coils 180 deg. out of phase as when they are in phase.

There is an application of selective differential relays for auto-transformers on interconnections which has not been touched on in this paper. Where interchange substations consist only of a grounded auto-transformer with only one line at each voltage, it is possible to use a selective differential ground relay, balanced by use of auxiliary auto current transformers for a through flow of ground current. The additional ground current supplied by the auto-transformer will prejudice the balanced relay toward the line in trouble, leaving the auto-transformer and its tertiary load connected to the good line. In making the balance it is necessary to assume that the through current varies inversely as the transformation ratio of the auto-transformer. This scheme has been in successful operation on our system for about two years.

One feature, not touched on in the present paper, which acts to discourage the wider use of potential-operated relays of the power directional type or residual volt-ampere type is the lack of any universal relation between power factor and fault conditions on the system, especially on interconnected systems. Phase angle between load current and phase voltage varies over a wide range under normal and abnormal operating conditions, without any faults on the system. Even under fault conditions the phase angle may vary nearly 90 deg. at the same location and is widely different at various locations even on the same system. The same statements apply to residual potential and ground current.

The above conditions explain the operating results given below which have been obtained by certain companies in this territory.

1. Power directional relays are of little value on interconnected systems.
2. Impedance relays are reasonably satisfactory.
3. Directional ground relays of the type using two current elements and connected up as per Fig. 17 in the paper under discussion have been remarkably satisfactory.

4. Selective differential relays have been very satisfactory when properly set and interlocked.

5. Directional volt-ampere relays have given some trouble due to variation in power-factor relations.

The foregoing comments are naturally based on operating experience under conditions that may or may not be general in the industry.

L. F. Kennedy: The crux of this whole situation is to maintain the stability of the system which in turn requires very rapid clearing of faults. This is also tied up with the accuracy that may be obtained, because without accuracy we cannot get down to minimum time settings.

Further, the bus sections must be treated as part of the line and whatever protection is provided necessarily covers these.

One point which has not been discussed is the protection of the power transformers used in the interconnections. These transformers today are, in many cases, of the three-winding type and the protection provided here is further complicated by the use of tap-changing arrangements.

The so-called impedance relay in its principle and theory appears very well adapted to single-line operation. However, we feel that there is still a great deal of development to be done before this relay is ready for final use by the operating companies. At the present time it appears that the adjustment and maintenance is more complicated than can be stood for a very extended length of time. Therefore, it appears that the manufacturers must continue their investigations, and I feel certain this is being carried on by the leading companies.

The use of ground relays, either of the quantitative or directional type, the directional type being polarized either by voltage or current as the conditions permit, have met with a very high degree of success, and operating conditions seem to indicate that more and more importance should be given to the protection against ground faults since with the higher-voltage systems we run into more ground faults than on any other type. Nearly every case of short circuit at the present day eventually goes to ground, and therefore in the final analysis the ground relay is the thing of greatest importance.

The situation, as it stands today, indicates that for parallel-line operation balanced hook-ups with the back-up protection necessary provided by over-current relays may be more desirable than anything else because of the simplicity and the fact that they are well known and it does not seem justifiable to ask the operating companies to spend too much time and money with schemes which are not in the final state of development.

In conclusion, let me emphasize once more that the main problem confronting both the operating companies and the manufacturers is to find some way of shortening the time necessary to clear a fault. If, as Mr. Jamieson has pointed out, we could catch the incipient fault it would be ideal. However, catching the incipient is still a problem of proper selectivity.

L. R. Janes: There are three questions that I should like to ask Mr. Graves concerning ground relays.

First: Are ground relays applicable for clearing "partial short circuits" on overhead systems such as we have in this territory? By a "partial short circuit" I mean a condition similar to that resulting from the breakdown of an insulator thus leaving only the pole or crossarm for insulation. The case of a conductor falling to dry earth is another example.

Second: As I understand it, the ground relay is only applicable for clearing phase-to-ground faults. Is phase-to-ground fault protection satisfactory and sufficient for overhead lines? In other words are practically all faults from phase to ground or does experience show that a considerable percentage are from phase to phase?

Third: Consider the case of a generating station supplying several substations located at points scattered along a transmission-line loop. If ground relays only are installed at the generating station on each of the two out-going lines and a fault occurs approximately half-way around the loop which is the point most remote from the generating station, will not the fault currents in each branch of the loop be approximately equal and thus cause both lines to open instead of only the one containing the fault?

F. D. Wyatt: On power systems using neutral resistance for fault-current limitation, the relay current during ground faults necessarily is of small value. The ground relay becomes of increasing importance on the power system using the neutral resistance for current limitation, and that its operation should be dependable is one of the difficulties to be reckoned with. The ground-relay scheme must involve a sensitive relay whose sensitivity and reliability depend largely on the range of fault currents for which it must operate.

The paper shows one of the factors controlling the range of variation, namely, variation in generating capacity and point of generation, which may cause wide variation in the magnitude of fault currents. The paper also brings out the complications which are necessary in the relay circuit to compensate for the wide range of fault currents. For ground relaying, the situation is further complicated by the wide variation possible in the resistance of the fault and also a variation in the number of grounded neutral points.

The ground relay should also differentiate between low-value fault currents and small residual currents which may result due to the character of the relay circuit and system connections. Ordinarily, the balanced protection applied to a pair of lines, it is assumed that the lines are of equivalent and equal impedance characteristics. This, however, is not always the case so that when lines are of unequal length it is necessary to make proportional adjustment for the distribution of current. The problem is a little more difficult if the lines are not of the same power-factor characteristic.

Another factor which enters into the setting of balanced line relays is the possibility of induced voltages being applied to a good pair of lines by external circuits adjacent to the balanced pair. That is, assume that there is a line which is a part of a good pair running adjacent to another circuit which is in trouble with a phase to ground fault. Due to the current in the faulty circuit, potentials will be induced on the balanced pair which will cause a circulating current to flow in the loop formed by the balanced pair. Then a current will flow through the ground relays and if they are set at too low a current value an incorrect relay operation on the pair of good lines will occur.

If I may, I should like to answer the last question of Mr. Janes. That situation can be taken care of by using directional ground relays instead of current ground only. At the power station or substation where neutral resistors are available, or neutral current can be measured, directional features can be secured where there is not a transformer bank or transformer neutral. This may be secured by using potential transformers arranged to give an inside delta potential which is the residual voltage at the substation.

B. M. Jones: (by letter) The scheme shown in Fig. 15 is admirably suited to our system, for it simplifies the present scheme of balanced parallel-line protection which we have been using, in that it removes several complications. On our system we are not confronted with small fault currents wherein these fault currents are less than the load currents, for our system is relatively compact and a considerable amount of ground current flows in all ground faults as well as short circuits.

Fig. 13 shows a diagram for directional line and ground protection for a single-circuit 3-phase transmission line. This particular scheme is standard with our company, and I believe that we were one of the first companies to adopt such a scheme. We have this scheme in use very widely on our 22-kv. system and to a limited extent on our 66-kv. transmission line. This scheme of directional ground protection was described by Mr. Dodds

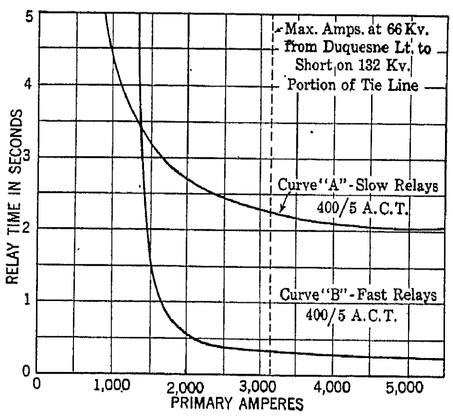
and myself in a paper presented before the Institute in Detroit in June of this year.

Fig. 25A shows a complete relay scheme applicable to a complex interconnecting system which uses thirteen relays for tying together two lines. This is a vast number of relays and a correspondingly complicated connection; and to my mind strenuous efforts should be made to simplify such a scheme. While such a scheme may look well on paper and may suit the engineers in the office, the relay trouble shooters are certainly going to have their troubles in maintaining such a mass of connections as this scheme shows.

While our company has used single-phase directional relays in all cases in the past, I can easily see that there are certain applications wherein the polyphase directional relay has some advantage over the single-phase relay. We have a certain case in mind on our own system now, where we are looking into the advantages to be gained through the use of polyphase relays.

It has been our experience, and I feel that other operating companies have encountered the same situation, that complicated relay schemes are hard to maintain and require a very high grade of skilled help, and eventually cause considerable trouble and inconvenience, and sometimes considerable embarrassment to those responsible for the relaying of the system.

Our company leans very strongly toward making all relay schemes as simple as possible to provide adequate protection and at the same time have as few a number of schemes as might be necessary.



The Duquesne Light Company has a 36,000-kv-a., 66/132-kv. tie line with the West Penn Power Company, our immediate neighbor, which line is 2½ mi. long. There is a transformer bank in our Colfax Power Station, which steps our bus voltage to 132 kv. for this line.

The particular relay scheme used for this is very simple and effective. The idea behind this tie was to hold the tie in unless there was trouble on the tie itself, or when serious trouble on either system hung on for an unreasonably long time. On this basis, the maximum benefit would be obtained from the use of the tie line.

The accompanying sketch shows the time-current characteristics of the relay scheme used, which is briefly the installation of two sets of over-current relays at each end of the tie line which are set alike in pairs.

One set of relays at each end of the tie line are "fast relays" and the other set "slow relays." The "fast relays" operate for trouble on the tie line itself on one side of the bank and will cause enough current to flow in the closest relays (closest electrically, from an impedance point of view), to operate, thereby breaking the tie at one end. The "slow relays" will operate for trouble beyond the bank on either side, and are set slow enough to allow the relays of the power company in trouble to clear the trouble. In case the power company in trouble does not clear itself of trouble within the time setting of the slow relays, they will break the tie, thereby relieving the good system from the difficulties of the system in trouble. The ground relays are set same as the fast relays, and of course operate for trouble on the tie line itself.

Our experience has shown that this relay scheme operates as it was planned to operate, and occasions have arisen whereby the slow relays have taken out the tie when the system in trouble did not cut the trouble clear promptly.

H. H. Green: (communicated after adjournment) The carrier-current protective scheme referred to brings into the protective-relay field principles which are new to this phase of power-system engineering. The pilot-wire scheme, which is the basic relay principle involved, is not new and is ideal for transmission-line protection. This relatively new carrier-current scheme has real possibilities and will require only an adequate operating record under service conditions before taking its proper place as a super-power system protective scheme.

The scheme outlined in detail, requiring the use of special and standard relays, is based on relay principles in common use. The need of a quantitative study of short-circuit currents, in order to apply and obtain the maximum benefits with the relays now available, is quite obvious. The development of the Method of Symmetrical Components, for studying fault conditions, has placed in the hands of the protection engineer a means of handling this difficult phase-to-ground short-circuit problem, and the application of this method to the calculating table permits the handling of phase-to-ground short circuits on complicated systems, as 3-phase short circuits have been handled. The calculating table is, therefore, made still more indispensable as the type of construction of the super-power systems will result in phase-to-ground faults being in the majority. The calculating table is more indispensable than the slide rule, in its field, in relation to the protection of a large system and should, figuratively speaking, be at the protection engineer's elbow.

The need of a quantitative study of the problem makes it desirable to use recording equipment in the field to obtain accurate measurements of the quantities involved. A form of oscillograph, which is automatically put in service at the time of the fault, lends itself to this type of investigation and such records are of real assistance.

H. C. Graves, Jr.: Mr. Bradley has described two features which may cause incorrect relay operation. The first of these brings out the fact that 3-phase core-type potential transformers cannot be used in general for relay protection, particularly when directional ground relays are used. Such potential transformers must be either single-phase transformers or of the 3-phase shell type. The second point made by Mr. Bradley is that directional relays may operate incorrectly if the overcurrent contacts open so slowly as to permit the directional contacts to close and cause faulty tripping before the overcurrent contacts open. One correction for this trouble is also indicated.

In the majority of cases where such trouble occurs, it will be found that it can be corrected by increasing the contact spacing of the directional element. It should be noted that this directional element need not be instantaneous, but need only be fast enough always to close before the closing of the overcurrent contact. Overcurrent relays of the ungeared type will open their contacts in from 3 to 4 cycles (60-cycle basis) after the relay is de-energized. This quick opening of the contacts permits the relay to handle the majority of cases described by Mr. Bradley without causing faulty operation. In those few cases where the contact spacing cannot be increased sufficiently to avoid the trouble, directional overcurrent relays may be employed. These have directional contacts connected in series with the upper pole circuit of the overcurrent element, thus preventing operation of the overcurrent element until power flow is in the direction which causes closing of the directional contacts. The overcurrent contacts are then permitted to trip the circuit breaker directly.

This arrangement is very simple but involves special design of the upper pole windings of the overcurrent element.

The diagram shown in Fig. 2, referred to by Mr. George, brings out the different operating characteristics of this relay depending upon whether the currents in the two coils are in phase or are 180 deg. out of phase. Curve *A* represents the in-phase condition, or the condition where currents flow out on both the good line and the bad line. Curve *B* illustrates the condition which would exist at the other end of the line, or the relay characteristics with the currents 180 deg. out of phase.

The point made by Mr. George relative to the necessity for having current transformers of good characteristics for operating residual relays is of importance. Residual relays have a relatively low volt-ampere burden, but the impedance is usually higher than the line protective relays because of the fact that lower current taps are used. As a result of this fact a phase-to-ground fault causes a voltage to be built up across the residual relays which tends to cause the fault current to circulate back through the bushing type current transformers in the good phases. Unless the characteristics of the bushing-type current transformers are good, this leakage current will be so appreciable as to affect the relay operation.

Mr. George also brings out the fact that the use of volt-ampere relays is hindered by the fact that the phase angle under fault conditions is quite variable. This in itself would indicate that the volt-ampere relays could be used to advantage on systems whose neutrals are grounded through a grounding resistor. This tends to establish a fairly constant angle between the residual voltage and residual currents. Thus advantage may be taken of the fact that the residual voltage and residual current invariably increase as the fault is approached.

Mr. Kennedy stated that "The so-called impedance relay in its principle and theory appears very well adapted to single-line operation." We are pleased to add that operating experience with relays of this type indicates that they also work out in practise. At the present time both types of relays can be used with the assurance that their operating characteristics are definite, and that they will therefore operate according to the adjustments made.

On complicated systems it is necessary to ascertain the distribution of and value of short-circuit currents in order to determine breaker ratings and relay settings. To make this study it is necessary first to determine the reactance or impedance values of the system, set up these values on a calculating board and read the short-circuit current for both maximum and minimum conditions of generating capacity. This involves a considerable amount of labor. Knowing the current values for the minimum condition of generating capacity, the relay setting of definite time relays may immediately be established. For inverse-time overcurrent relays this is not the case since the relays must be set so as to secure selectivity under the maximum condition of generating capacity as well as minimum condition.

After the short-circuit study has been made, it is as simple to determine the setting and operating time of the impedance relays as is the case with inverse-time overcurrent relays. The fact that the impedance relay is practically independent of conditions of generating capacity simplifies the determination of the time required for the operation of the relay.

The first question asked by Mr. Janes can best be answered by the statement that the present design of ground relays permits them to operate when the current flowing to ground is such as to cause 0.5 ampere to flow in the secondary of the current transformers. This is somewhere in the neighborhood of 12 per cent of full-load current. These relays are therefore much more sensitive than can be the relay protecting against phase-to-phase faults. If the fault is such as not to permit this value of current to flow, the additional load imposed on the transmission system is probably so small as to be negligible until the faults develop into a phase-to-phase fault. When this happens the phase protective relays will clear the fault. In answer to the second question, I should say that the general concensus of opinion today is that both phase-to-phase and phase-to-ground fault protection is necessary. If only one type of protection be used, it should be the phase-to-phase protection. The greatest majority of faults on a system consist of phase-to-ground faults, but on most systems phase-to-phase faults will occur which will not tend to operate the residual relays.

A general answer to the third question is difficult in view of the fact that almost every case must be handled individually. In general, for systems of this type, residual relays will not materially assist in reducing the relay time unless the system is similar to that shown in Fig. 10. On the average system where the loop is grounded at only one end, and particularly where the pole hardware is not grounded and no overhead ground wire is used, residual relays will be advantageous because of their increased sensitivity, but in general will not cause any quicker clearing of phase-to-ground faults than will the phase protective relays in cases of phase-to-phase faults. However, since the distance between stations is so short as not to permit the application of the impedance type of relay, it would seem possible to apply pilot-wire protection, at least to the shortest sections, and thus reduce the number of selective settings necessary.

Relative to the selectivity of operation of the residual relays, on systems as described by Mr. Jones, the treatment must be very similar to that used for protecting against phase-to-phase faults. For parallel lines the residual relays are usually cross-connected. The exception to this is the system described in Fig. 10 where the residual relay acts somewhat in the nature of an impedance type of relay so that the relay closest to the fault will always clear first thus assuring selectivity even in case of parallel lines.

Mr Wyatt has mentioned the problem which has been met by several operating companies wherein a faultly line induces a current in one of a pair of parallel lines, thus offsetting the balance in this supposedly balanced pair and causing operation of the relays. This usually occurs only for phase-to-ground faults, and one solution consists of increasing the settings of the balance relays. This solution is undesirable in view of the fact that it reduces the sensitivity of the ground relays, thus doing away with one of their major advantages. A second suggested solution consists in balancing the unbalance in the two pairs of parallel lines. The unbalanced current in the faulty pair of parallel lines will invariably be greater than that in the good pair. This difference in unbalances will cause a set of contacts to close which will permit the operation of the relays on that pair of parallel lines which has the greatest unbalance. The objection to this scheme lies in its complexity, and in the fact that the scheme cannot take care of unbalances at the neighboring stations. These relays must still be set high to avoid faulty operation. The relay solution here as in many other relay problems consists in designing the system so as to permit proper relaying without excessive cost.

Mr. Jones has found objections to the system of connection as shown in Fig. 25, because of its complexity. This we believe is just, and this system of connection should never be installed except in those extreme cases where necessary. However, as mentioned by Mr. Green, each part of the scheme consists of relay principles which have been in use for some time and have been proved, and thus an experienced maintenance crew guided by the short-circuit study and operating experience, should have no difficulty in determining the cause of faulty relay operation.

In conclusion, I should like to add that simplicity in the protection schemes invariably gives the best results. However, to be able to employ simple relay schemes, it is essential that the system layout be such as to permit these simple schemes to be used. Relay application is complicated because all systems are different. The system grows up and as it grows the relays are changed so as to take care of the newly developing conditions. The best results can be obtained only when the planning of the system and the scheme of protection go hand in hand.

Alternator Characteristics Under Conditions Approaching Instability

BY JOHN F. H. DOUGLAS[1] and EDWARD W. KANE[1]
Associate, A. I. E. E. Associate, A. I. E. E.

***Synopsis.**—In this paper the comparatively recent discovery of generator instability is discussed. A method of testing synchronous machinery in the unstable as well as in the stable range is described. The results of tests performed on two machines is shown and discussed. The conclusion is drawn that the design of customary machines will have to be improved, synchronous condensers installed on many long lines, or inefficient underloading of units will have to be tolerated.*

Introduction

Until recent years the loads on power systems were with a predominately lagging current. While the regulation of the generators was sometimes quite poor, nevertheless the operation showed high stability and the field rheostats were adequate to control the voltage without loss of synchronism. Perhaps because of this fact, and perhaps for other reasons, textbooks have shown practically no diagrams or full-load saturation curves for leading power factors. The student might well obtain the impression that the solution of the problem of regulation for such power factors would be carried out without difficulty, but when one attempts to carry out the solution, one meets with several obstructions of a theoretical nature.

Of late years the voltage and length of transmission lines have been increasing and the number of interconnections growing. Consequently the leading current load is becoming quite an item. At the same time due to attempts to improve customer power factor the lagging current load has shown a tendency to decrease. As a consequence, some curious phenomena have been noticed and reported: 1. A very unstable voltage on light loads when the line charging current is carried by too few units. 2. Inadequate field rheostat resistance to keep the voltage down. 3. The combination of lines and generator becoming self-exciting, that is, a resonance between the inductance of the machine and the capacity of the line, giving high voltage with the field circuit open. 4. Generators remaining in step with small reverse field excitations. 5. Generators slipping a pole when the reversed field excitation is increased, and before the voltage is brought down to normal. When this pole slipping takes place, there is a surge which causes the voltage to rise to considerably above normal.

The difficulties met in attempting to apply the A. I. E. E. rule for leading current loads is well illustrated in Fig. 1. The curve $O X$ is the no-load saturation curve; $F Y$ is the full-load zero power-factor lagging saturation curve, and $F Z$, the full-load unity power-factor saturation curve. The zero leading power-factor full-load saturation curve is shown by the line $A B C D$, or the line $A B C E$. The segment $A B$ is as much above the no-load saturation curve as the line $F Y$ is below it, as required by the A. I. E. E. rule. For saturations below this point, one is in doubt as to just how to proceed, but if it be assumed that the synchronous impedance is a constant, the segment $B C$ would be drawn parallel to the line $O X$. For voltages below $O C$ we meet another difficulty. If we continue the line toward the point D, we have a characteristic which, unlike the lagging characteristics, does not pass through the point F. If we reverse the segment $C D$, we are unable to account for the operation with reversed field currents and we must imagine a sudden 180-deg. shift of phase at the point C.

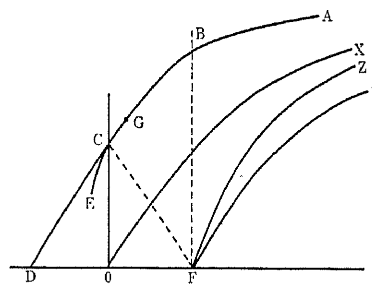


Fig. 1—Illustrating Difficulties in Estimating Zero Power Factor Leading Saturation Curves

With the peculiar behavior of synchronous machinery reported and the obvious defects in the more usual theory before us, we determined to make some tests with leading current conditions and if possible, try to extend them into the region of unstable operation.

Preliminary Tests

Our first tests were of a qualitative character. We sought to verify for ourselves just what took place when a generator lost control of its load. We connected an a-c. generator to a synchronous motor load, but did not take power from the motor. We overexcited the motor, loading the generator with leading current of low power factor. We included a field ammeter, armature ammeter, and voltmeter in the generator circuits. We attached a G. E. slip meter to the syn-

1. Both of Marquette University, Milwaukee, Wisconsin.

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chronous motor shaft, which we excited from the same 60-cycle supply that furnished power to the synchronous motor which drove the generator being tested. The amount of leading current was held roughly constant and varied the generator field current and generator voltage. The characteristic $A\,B\,C\,E$ in Fig. 1 was obtained. At the point E there was a surge of voltage and current, the generator forged ahead one pole or the motor slipped a pole as indicated by the slip-meter differential turning 90 electrical deg. The voltage after the surge corresponded to the point G.

This experiment was considered to prove, in a general way, the results previously reported, and to indicate that further tests were worth while.

Tests of Generator Characteristics by a Pump Back Method

First of all it was determined to employ an opposition method of testing, in order to obtain, if possible, characteristics of the unstable condition of operation. This procedure was successfully used by one of the authors in testing synchronous motors in their unstable range, and reported on in the A. I. E. E. Transactions, 1925; p. 164. It was found that the connections in Fig. 2 were suitable. The generator (1) was directly connected to an identical machine (2) with a movable stator controlled by the hand wheel (3). These machines were 15-kv-a. 1200 rev. per min. machines rated at 220 volts with a Y-connection. Machine (2) absorbed the power generated by (1). The losses were sometimes supplied by a d-c. motor belted to the set, and sometimes, from the connection shown to the 60-cycle line. The amount and phase of the current output of the generator could be controlled by the hand wheel (3) and rheostats (4) and (5).

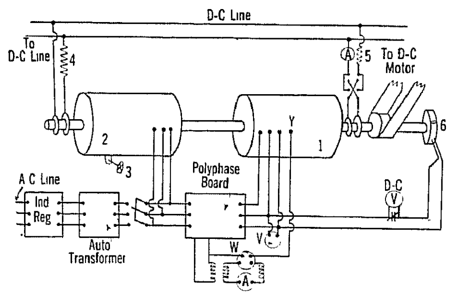


Fig. 2—Connections for Determining Complete Excitation Characteristics of Alternator

The output of the generator was measured by a polyphase wattmeter; sometimes by the three-wattmeter method, using the neutral point on one machine. The line current and voltage were measured with the aid of a polyphase board. The phase angle of the terminal voltage with respect to the pole axis was measured with the contactor (6). This contactor was the usual point-by-point wave form apparatus, and was connected in series with one phase of the generator and a d-c. voltmeter, which was shunted by a condenser. The movable arm carrying the contacts could be turned about and their position noted on a degree scale. They were turned at all times so that the voltmeter gave a zero reading. The shift of the contacts from no load to the point under observation indicated the amount that the pole axis shifted with respect to the terminal

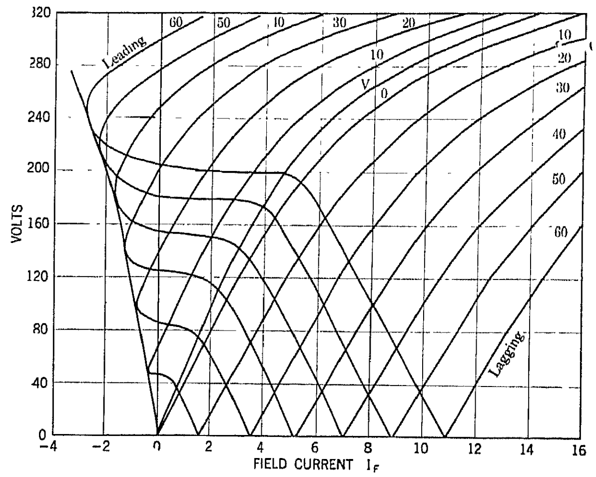


Fig. 3—Excitation Characteristics of Alternator Zero Power Factor Leading and Lagging for Constant Armature Current

voltage. This use of the contactor was developed by Messrs. Edwin Baldwin and Earle Lashway when seniors at Marquette University.

In the first series of tests, the wattmeter was at all times kept at zero by the hand wheel. Currents were circulated by maintaining a difference in the excitation

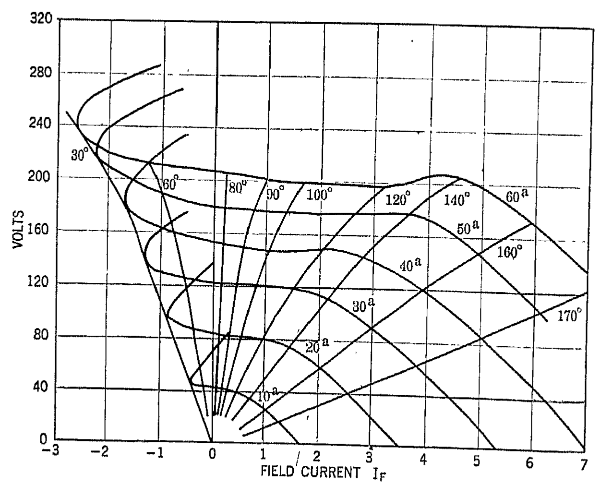


Fig. 4—Zero Power-Factor Characteristics Leading Current in Region of Unstable Operation, for Various Armature Currents and Various Angles of Pole Slip

between the two machines. Runs were taken for armature currents of 60, 50, 40, 30, 20, and 10 amperes. Voltage, field current, and phase shift were recorded for each run. Owing to the fact that when the generator field was large, the motor field was small, and *vice versa*, the voltage seldom exceeded 270 volts. For the higher

voltages, therefore, the set was synchronized with the a-c. line. The data were in such form that it could be directly plotted in Figs. 3 and 4. Fig. 3 shows the voltage characteristics for zero power factor, Fig. 4 shows also the phase displacements in the unstable range.

It is to be observed that stable operating condition is shown with reversed current in the field, also that the lagging and the leading characteristics join at a common point F, and that the shift of 180 deg. is only gradually accomplished in the unstable range. A

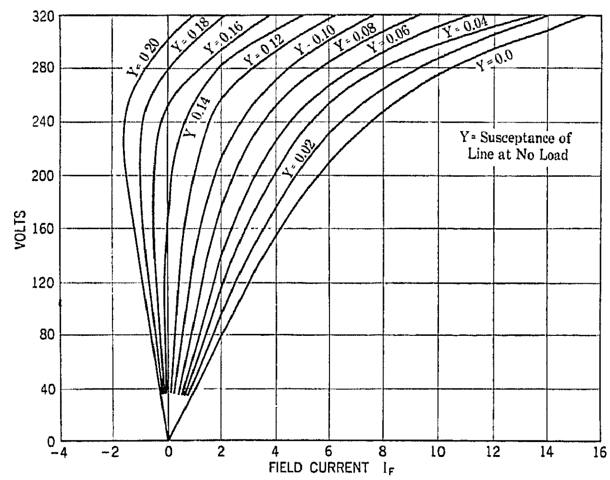


Fig. 5—Excitation Characteristics of Alternator at No-Load and Various Line Capacities

phase shift from 30 deg. to about 160 deg. occurs at a practically constant voltage. These "nose" shaped generator characteristics are believed to be novel.

Since a transmission line connected to a generator at no-load represents a zero leading power-factor load of constant ratio of amperes to volts, it was thought to be of interest to take a series of cross curves from Fig. 3 representing constant equivalent single-phase "Susceptances" of values from 0.00 to 0.2 in steps of 0.02 amperes per volt. These cross curves are plotted in Fig. 5. It will be seen that with a charging susceptance of large value, the characteristics are quite steep and in some cases practically vertical. Under these conditions, voltage control is difficult. If it is not feasible to use synchronous condensers on such a line and under-excite them at light load, then it will be impossible to shut down too many units at light load. Of course if a considerable improvement in generator design is made, this conclusion may be modified.

The second series of tests was made at a current of 40 amperes, practically full-load rated current. For convenience, at voltages of less than 270 volts, each run was made with a constant phase displacement between the two machines. Above 270 volts, each run was made for a constant terminal voltage. In each run, the power factor was varied from zero lagging to zero leading by a proper variation of the two field rheostats. For each run the terminal voltage, power factor, and phase displacement of the rotor was plotted against the field current. Cross curves were taken from these for constant power factors and constant phase displacements of rotor. Curves for 0, 70, and 90 per cent lagging, and for 100, 90, 70, 50, 20, and 0 per cent leading power factors were taken. Curves for 10, 20, 30, 40, 50, 60, and 90 deg. phase displacement were taken. All these curves are plotted in Fig. 6.

It is to be observed that all the full-load saturation curves pass through one common point F; also that for power factors of less than 20 per cent leading current, it is possible to obtain stable operation with reversed field current. The line $E\,S\,F$ passes through all the points where the curves are vertical and may be taken as the limit of stable operation. Below and to the left of this line, generator operation is unstable; that is, it will forge ahead a pole if it is free to do so. The phase displacements of the pole axis from the terminal voltage are small in the stable operating range and are considerably less at high saturations.

The hope for improved design and increased stability consists of being able to extend the nose of these curves toward the region of reversed field currents, and to lower the lower edge of this nose at the place where it intersects the Y-axis. Attention will be called in a later paragraph to the constant of the machine, which requires improvement.

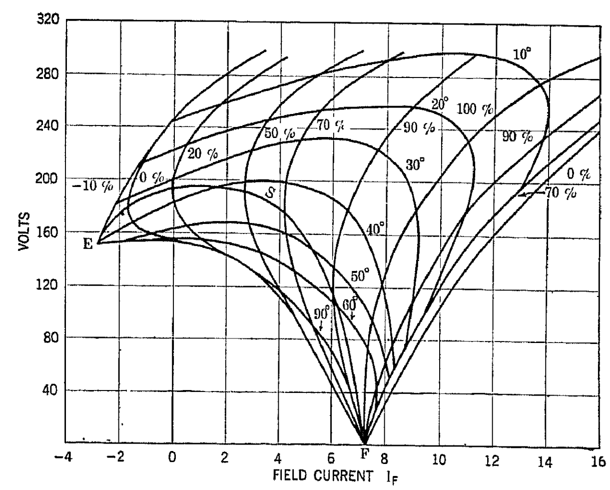


Fig. 6—Full-Load Saturation Curves by Test Loci of Constant Power Factor and Pole Slip Angle. Locus ESF of Stability Limit

Tests of Generator Stability with Direct Loading

In the endeavor to determine the locus of stable operation, such as $E\,S\,F$ in Fig. 6, by direct loading and actual observation of pole slipping, we took a 5-kv-a., 1800-rev. per min. 220-volts, three-phase Northwestern machine and connected it according to the diagram in Fig. 7. In this figure (1) is the alternator to be tested, driven through a belt by the d-c. shunt motor (2). The alternator delivered its power to synchronous motor (3), and this, in turn, to the alternator (4) and

the a-c. line. By controlling the rheostat (5) in the field of the d-c. shunt motor the amount of power circulated could be controlled. The amount of leading current taken from the alternator could be controlled by the field rheostat (6) of the synchronous motor. The field of the alternator (1) was controlled by reversing switch (7) and rheostat (8). For convenience each run was taken at a constant field current of the alternator tested.

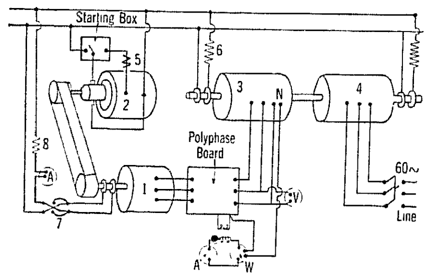


FIG. 7—CONNECTIONS FOR DETERMINING POINT OF POLE SLIPPING IN AN ALTERNATOR

For each point of data, the field rheostat of the d-c. motor was weakened until the generator slipped poles. This pole slipping was easily identified by the current and voltage surge which took place. Some practise was required, however, to secure readings at the point just before the pole slipping took place. It was observed that with reversed field current on the generator, only a small load could be carried without pole slipping

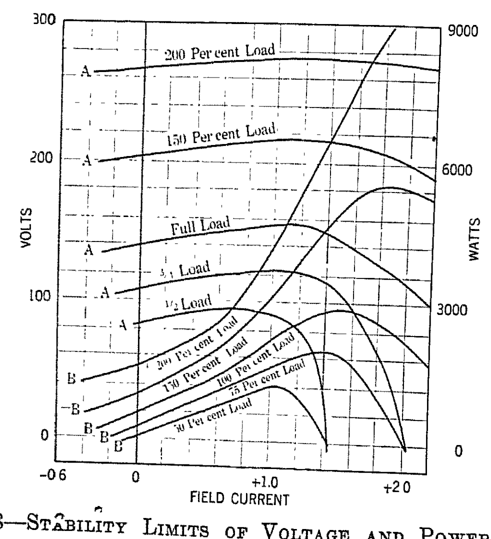


FIG. 8—STABILITY LIMITS OF VOLTAGE AND POWER IN AN ALTERNATOR FOR VARIOUS CURRENT LOADS

taking place. Under these conditions, the generator slipped only one pole and regained synchronism. When the fields were excited in the normal manner, a considerably greater load could be carried without pole slipping; but when the critical load was exceeded, the generator fell out of step completely and continued to slip poles.

Readings of generator voltage and watts were taken for the slipping point and plotted against the armature currents, for six runs, during which the alternator field currents were respectively 2, 1.5, 1.0, 0.5, 0, and -0.5 amperes. Cross curves were taken from these for armature currents of 2, 1.5, 1, 0.75, and 0.50 times rated current. The cross curves thus obtained are shown in Fig. 8.

The curves shown agree in form fairly well with the curve $E\,S\,F$ in Fig. 6. The voltage of the generator is too high at conditions of large leading current. The chief conclusions to be drawn from these curves are as follows: (1) The criterion of stability assumed,—namely, a vertical volt field-current characteristic,—is borne out. (2) Generator operation is unstable below a voltage which varies in proportion to the current load on the machine. (3) To operate at normal voltage in a stable manner, the leading current load must be kept down to a certain fraction of the rating connected to the line. It is to be hoped that improved generator design will increase that fraction.

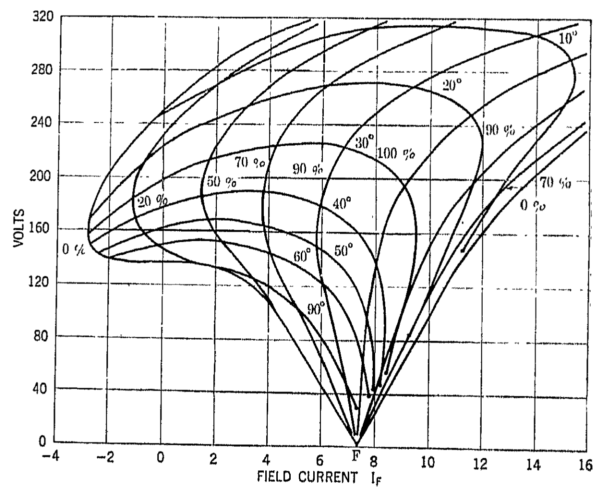


FIG. 9—FULL LOAD SATURATION CURVES COMPUTED BY BLONDEL. TWO REACTION DIAGRAM, LOCI OF CONSTANT POWER FACTOR AND POLE SLIP ANGLE.

PREDETERMINATION OF GENERATOR CHARACTERISTICS WITH LEADING CURRENT

In the A. I. E. E. JOURNAL for February 1927, (p. 109), one of the authors proposed a method for computing the performance of synchronous machines. It was thought that it would be interesting to compute a series of curves such as shown in Fig. 6 by the method there outlined. It was felt that in view of the unusual and novel shape of the curves in Fig. 6, an agreement would give a satisfactory confirmation of the theory. The constants of the machine tested in this paper for two-phase connection are reported in the article cited. For the three-phase connection the following were assumed:

Direct armature reaction 7 amperes field current equivalent to 40 amperes in the armature. Transverse armature reaction, 3.5 amperes in the field equivalent to 40 amperes in the armature. Direct reactance 1/3

ohm per phase of Y, transverse reactance zero, and resistance 1/6 ohm per phase of Y. Saturation curve is as shown in Fig. 3.

With the constants in the above paragraph, the characteristics shown in Fig. 9 were computed. These should be compared with Fig. 6. We consider the agreement is very good, and believe that further theoretical studies of synchronous machines should be based on some form of the Blondel two-reaction theory.

The extent of the "nose" of the curves and the lower intercept of the nose on the Y-axis seems to depend chiefly upon the constant of transverse reaction.

Conclusions

In this report various remarks have been made to point out results of significance. The most general conclusion to be drawn is this: By a reduction of the value of the transverse reaction with improved design, there is a hope for machines of greater stability and consequent improved behavior under conditions of low leading power factor.

The problem of stability is likely to become more acute as the voltages, lengths of transmission line, and the number of system interconnections increase, so that it is hoped that the manufacturers will be able to improve the stability of their machines.

Discussion

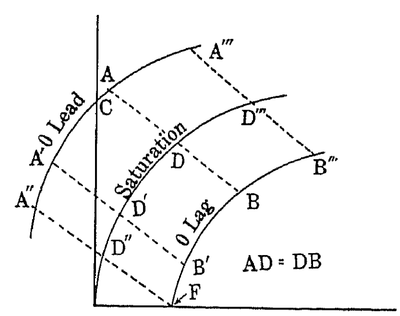
B. A. Behrend: This paper is timely and opens up a number of points which I wish to enumerate. First, it calls attention to the method of the A. I. E. E. for the determination of regulation and states that the method recommended for zero leading power factor is in error. As I have been instrumental in introducing the zero-power-factor method for the determination of the regulation of alternators,[1] I here state that the correct method, or at least the method which I recommended, consists in shifting the entire saturation curve along the line AB, either below the saturation curve for lagging currents, or above for leading currents.[2] This is the Potier-Behrend method which has been used by us continuously for twenty-eight years. Refinements of this method have been made from time to time but the fundamental simplicity and accuracy have been maintained. It is regrettable that the Standards Committee appears to have departed from this method as would be indicated by the statement made by the authors.

So far as I know the curves produced by the authors are novel. My second point deals with their attempt to join the leading-current zero-power-factor regulation curve to the point F in their Fig. 1. In checking the curves of their Fig. 3, by the Potier-Behrend method I find a good degree of agreement with their curves. With a leading-power-factor load of a given amount the authors found that the generator would stand a small amount of negative excitation after which "the generator forged ahead one pole or the motor slipped a pole." Now, it would have been interesting if they had attempted to prevent this action so as to prevent the leading zero-power-factor curves becoming discontinuous. Negative rotor excitation can be compensated by leading stator excitation so long as the two fields remain in step. Theoretically within limits it makes no difference on which member the excitation is applied.

Twenty-five years ago we used to design alternators with good regulation so that it was not exceptional to have a generator with a short-circuit current six times the normal current and with a very "stiff" field. On such generators it is possible to run a negative excitation without the slipping of the rotor. Such curves have been run on fly-wheel type generators with great inertia and they have confirmed the Potier-Behrend method of regulation. Such tests should now be repeated on modern alternators with large armature reaction by resorting to special methods to keep the generator from falling out of step. There are several ways in which this can be done.

Thirdly, I should like to comment on the suggestion of the authors advising that improvements in alternator design should be made to secure greater stability on long lines of great capacitance. It is very essential that this be done but it would be regrettable if history had to repeat itself and if large generators would have to be built again with strong fields instead of strong armatures. The remedy might be worse than the disease.

The problem of stability is by no means a new one and much could be learned in the present predicaments from past experience. Perhaps one of the most difficult problems was the design of the generating plant for the United States Steel Corporation



of its Indiana Steel Company's plant at Gary, Indiana, where fifteen 3000-kv-a., generators are operated in parallel by gas engines. In such cases it is necessary to take into account the stability of the generators so far as overload is concerned; and the stability in regard to oscillations which are dependent on the electric characteristics of the generators and on the total inertia of the unit. The generator and gas engine have a natural period of oscillation which can be calculated and this period must not coincide with any "forced" period which may happen to be in the system. I had charge of the design of this plant and it is gratifying to state that the calculated frequencies agreed so well with the actual frequencies that, in spite of light flywheels and virtually no damping in the pole pieces which were solid without copper dampers, the plant operated perfectly from the start. Now, the overload margin of modern generators is much curtailed on account of the weak fields and their natural period of oscillation is greatly increased for the same reason so that conditions of resonance are likely to disrupt the system. Blocking of governors has had to be resorted to in some of the largest plants to avoid such resonance. If a generator, slightly displaced from its position of equilibrium, performs an oscillation the period of which is nearly equal to the surge frequency of the line, no stable operation can be expected. Either a weaker or a stronger field, or a greater or smaller moment of inertia, would or might improve such a condition. It was my practise to test the generators for their natural frequency where the unit was used in connection with gas engines or steam engines and where

1. The Factors which Determine the Design of Monophase and Polyphase Generators," by B. A. Behrend, *Electrical World & Engineer*, Jan. 20, 27, Feb. 3, 1900.

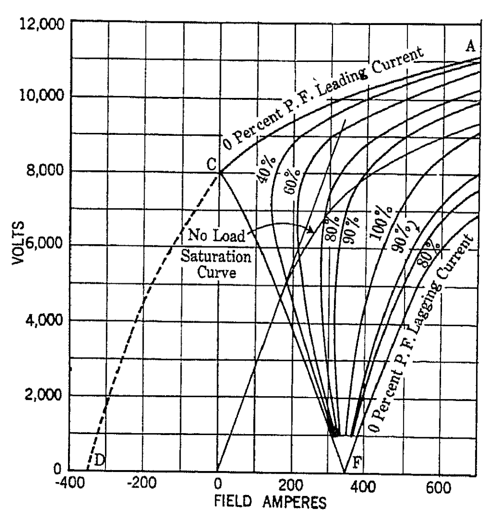
The Experimental Basis for the Theory of the Regulation of Alternators, by B. A. Behrend, Transactions A. I. E. E., Vol. XXL, 1903, p. 497.

2. "Sur la Réaction d'Induit des Alternateurs," by Alexandre Potier, *L'Eclairage Electrique*, July 28, 1900. This paper is based on B. A. Behrend's data and its Fig. 2 shows the regulation curves for zero lagging and leading currents.

there was a pronounced forced frequency going to be in the system. A similar course should be followed in connection with units which have to operate on long lines so as to predetermine as nearly as possible all natural and forced frequencies which are to be found in the system. In this direction much can be done to improve the operating stability.

While refinements in the determination of the methods of regulation are desirable, at least for the designer, there is little hope that such refinements may lead to the curing of the intrinsic problems of instability which are characteristic of all dynamic systems in which energy is alternately released and stored and which have several degrees of freedom.

J. Strasser: We do not agree with the authors that there should be any difficulty from a theoretical nature when plotting saturation curves at leading power factor. We treated the problem of stability of turbine generators in an article in the *Electric Journal*, August 1926 issue, and used the Potier triangle when plotting the saturation curves and did not have any difficulties. These curves (shown herewith) were obtained by pure theoretical considerations and under the assumption of constant magnetic resistance in any radial direction which can be done in the case of a turbo-generator. The curves obtained



by test by Messrs. Douglas and Kane confirm the correctness of our theoretical curves and also our conclusions drawn. We found that of the 0 per cent power-factor leading-current saturation curve the part $C\ F$ corresponds to a slip of one pole and that the slip must occur in the point C. This means that for non-salient-pole machines the nose of the 0 power-factor saturation curve shrinks together to a point. For salient-pole machines the slip occurs gradually from 0 deg. at the point C to 180 deg. along the nose and even crosses the 0 field-current line. The authors stated that the nose depends largely on the constant of the tranverse reaction which is in agreement with our conclusions.

We are, however, not of the same opinion as to which is the limit of the stability. This paper seems to base it on regulation and uses the point of change in curvature of the saturation curve at constant power factor and armature amperes as a criterion. This point of minimum field current and constant power factor appears certainly in my curve at leading current only, but what are the limits for lagging current?

Sometimes a high short-circuit ratio of 1.1 or higher is called for and actually we do not need it. We now have generators in operation with a short-circuit ratio as low as 0.75 and we have never experienced any trouble. The power stability depends on the combined characteristics of net work and generator. The only constant is the field current whereas everything else changes. When the system characteristic is known, it has to be superimposed on the generator characteristic at a given excitation and the combined characteristic determined as has been shown in the article in the *Electric Journal*. This will hold for leading as well as for lagging power factors.

M. W. Smith: The portion of the Curve $A\ B\ C\ D$ below the point C, referred to in Fig. 1 of the paper, is of academic interest only, because it is in the range of instability. It is usually not considered safe practise to operate even salient-pole machines with reversed excitation. However, from a theoretical standpoint, it seems logical that this curve should continue to the point D if an external power factor of 0 per cent leading could be maintained. This requires an infinite capacity with 0 resistance as the point D is approached. The fact that tests have shown a tendency for the curve to approach the point F below the point C, simply indicates that 0 per cent power factor is not being maintained. The internal power factor of course, will not be of 0 per cent leading, but will be 0 per cent lagging when zero voltage is reached. The leading-power-factor curve, of course, must reach the point F at zero voltage, because the internal power factor of the machine will be 0 per cent lagging, but whether the leading curve goes to the point F through the point D, or some other intermediate point, depends on the power factor of the leading current at the low voltage.

The authors refer to a hope of improved design that will give greater stability under leading-power-factor operation. This condition is hardly one of improved design, but one of special design. Present tendencies in design are towards low cost and high efficiency, which usually result in low gap inductions and high armature reactions. This tendency, of course, is contrary to inherent stability, except as corrected by increased air-gap length. Where leading-power-factor operation is not required, high efficiency and low cost are the important factors. On the other hand, where stability is the paramount consideration, machines of special designs are required. This, however, is a matter of design proportions to meet a special condition, and should not be considered as a general improvement in design, because other factors are usually more important than stable operation at leading power factors. Except in the case of very large high-speed machines, no difficulties have been experienced in the past in producing machines for any desired degree of stability under leading-power-factor operation.

J. F. H. Douglas: Mr. Behrend's diagram showing the reversal of the Potier triangle is very interesting. Mr. Behrend makes the statement, that while the parts showing reversed excitation, are not important, yet they can be predicted by the Potier triangle. I don't know whether Mr. Behrend considered the resistance drop in using this, but the diagrams I have seen worked out give this sort of relationship using the Potier method and do not lead to even slight reverse-field excitations, but look like Mr. Strasser's diagram.

The Potier method is inadequate to show that sort of thing, but is an improvement over the A. I. E. E. rule.

I heartily agree with Mr. Behrend and Mr. Newbury as to the question of the effect of relative pole and armature strength.

It was very interesting to note in Mr. Newbury's remarks that approximately double stability was obtained at only a 10 per cent increase in cost. It is to be hoped that by other methods to be developed, the same can be done for less cost.

An intimation was made during the discussion that the Potier triangle is able, so far as regulation is concerned, to duplicate results with quite considerable accuracy. It does not appear, however, that it checks phase displacement with the same accuracy that it checks the voltage-field-current relationship. Inasmuch as the Institute has defined the ratio of torque to phase displacement as a fundamental constant it would be of interest to know whether the Potier method does so check this ratio of torque to phase displacement. So far as the particular machine reported on is concerned, neither the A. I. E. E. method nor the Potier method checks the phase angle as closely as the Blondel method.

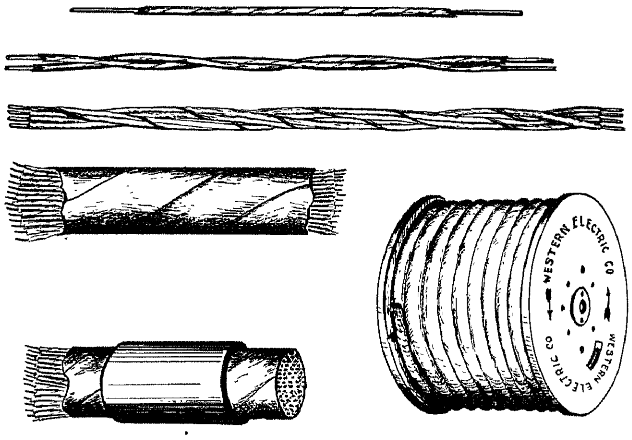
Recent Developments in the Process of Manufacturing Lead Covered Telephone Cable

BY C. D. HART[1]
Member, A. I. E. E.

THE manufacture of telephone cable consists essentially of insulating copper wire with paper, twisting two insulated wires together to form a pair, again twisting to form a quad if quadded cable is to be made, stranding these pairs or quads into a compact core, removing moisture, covering the core with a continuous sheath of lead or lead alloy, testing the completed cable, and packing it for shipment.

In order to bring out clearly some of the recent developments in manufacturing processes it is necessary to review the beginning of the art.

The idea of using cables for telephonic communication goes back to about 1878. In a talk given in London by Dr. Alexander Graham Bell he stated: "It is conceivable that cables of telephone wires could be laid under-



Steps in the Manufacture of Lead-covered Telephone Cable

ground, or suspended overhead, communicating by branch wires with private dwellings, country houses, shops, manufactories, etc., uniting them all through the main cable with a central office where the wires could be connected as desired, establishing direct communication between any two places in the city."

About two years later or in 1880 the idea became a fact and wires enclosed in sheath were used across the Brooklyn Bridge.

The insulation used on these early cables was gutta-percha or rubber but these materials were not very satisfactory for land telephone cables. A little later sisal and cotton were used and the cable core was impregnated to prevent the entrance of moisture and then drawn into successive lengths of lead pipe previously extruded and laid out in straight pieces, the different lengths being then joined together by means of plumber's joints. Impregnation was resorted to because it was difficult to obtain a lead sheath which was entirely free from defects.

By about 1890 paper ribbon had been introduced as a substitute for cotton and similar insulations effecting, of course, a great saving in space and therefore in sheathing material and cost.

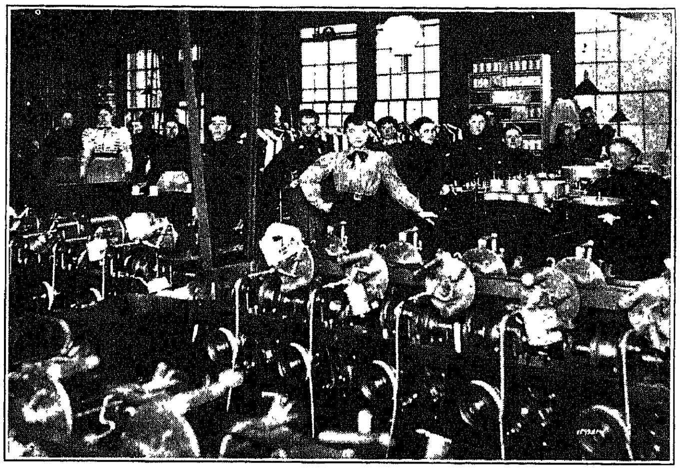


Fig. 1—Old Insulating Department About 1892

Fig. 1 shows a group of insulating machines used about 1892. With these machines paper ribbon was wound from a spool mounted eccentrically with the wire and the insulating speed was necessarily very slow.

Fig. 2—Old Twisting Department About 1890

Fig. 2 shows the twisting machines used at that time for twisting pairs. These machines were crude and operated at a low speed.

1. Western Electric Co., Kearny, N. J.

Presented at the Regional Meeting of District No. 5 of the A. I. E. E., Chicago, Ill., Nov. 28-30, 1927.

Fig. 3 is of an old stranding machine consisting of one drum only as the cable cores were built up one layer at a time and the core was run through the stranding machine as many times as there were layers in the finished core.

The old process of pulling cable core into lead pipe is illustrated in Fig. 4. This picture was posed a few

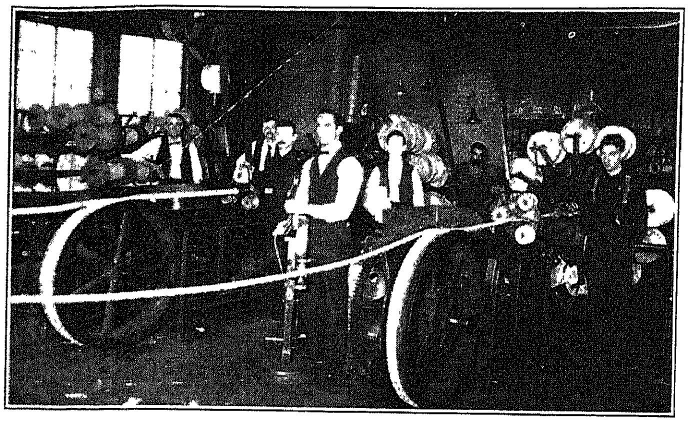


Fig. 3—Old Stranding Department About 1890

years ago, and the man standing in the foreground was one of a gang who formerly did this work.

A forward step in design of insulating equipment was made with the use of pads concentric with the wire which permitted very much higher insulating speeds and very much reduced paper breakage. The twisting

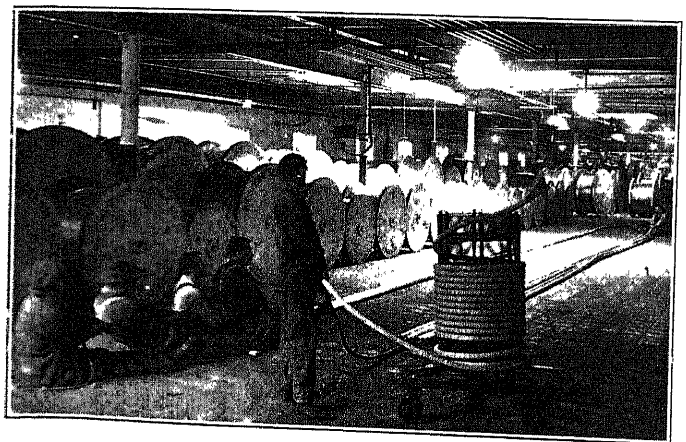


Fig. 4—Pulling Core Into Lead Pipe, Method Used Prior to 1894

machines were also modified to reduce uneven twisting and permit greater speed.

Another step was the development of multiple drum stranders permitting a number of layers or complete small cables to be made in one operation. Also, extrusion presses were improved so that a continuous sheath of lead alloy could be extruded directly on to the cable core eliminating the pulling in operation.

During the period from about 1900 to about 1920 many changes were made to increase output and improve the quality, also to permit of the use of thinner and narrower insulating papers so that a greater number of pairs of wires could be placed within the same cross-sectional area tending greatly to decrease the cost per circuit.

Cables made about 1888 contained 50 pairs of 18 gage conductor. By about 1902 improvements had been made which permitted 606 pairs of 22 gage wire to be put into a sheath of 2⅝ in. inside diameter which is the maximum size of sheath which has been found generally economical in telephone plants in this country.

By 1912 further improvements in equipment made it possible to use insulating paper of even smaller dimensions and to get 909 pairs of wire into the same diameter of sheath.

On account of increased congestion in the densely populated sections of the larger cities, there was a continued demand for more pairs of wire per cable, and in 1914 the first 1212 pair 24 A. W. gage cables were produced. This 24 gage wire was insulated with paper 5/16 in. wide and 2½ mils thick. The mutual capacitance between the two wires of a pair in this cable averages about .079 microfarads per mi. which allows a normal margin below the guaranteed value shown in Table I. The insulation withstands a potential test of 500 volts (maximum instantaneous value). The increasing number of pairs per cable and the corresponding decreasing cost per mi. of circuit resulting from the changes described is shown in Figs. 5 and 6.

With the growth of large office buildings and further increases in the demand for telephones in the great cities, even 1212 pairs of wire per cable were in some cases found to be inadequate, and in answer to the demand a cable has been developed containing 1818 pairs of 26 A. W. G. wires within a sheath having an inside diameter of 2⅝ in.

These wires are insulated with paper 7/32 in. wide and 1¾ mils thick by the use of specially designed insulating heads and, instead of being stranded in reverse layers as is the case with older types of cables, they are first stranded in groups of 101 pairs, 18 of these groups being then cabled together to form a compact core.

This method of cabling called the "unit" type to distinguish it from the layer type, has several advantages, particularly in splicing in the field. Development work on this 1818 pair cable is not yet complete but there is no reason to doubt that, if there is a demand for a 2400 pair cable, the demand will be met.

For convenient reference Table I has been shown giving the specified limiting characteristics of some of the standard types of non-quadded cables. From the table it will be seen that the larger gage cables are used mostly for trunk work and the smaller gages for connections to subscribers. While the electrical characteristics of these non-quadded cables are of prime importance, they do not demand quite the extreme re-

PRINCIPAL STAGES IN THE DEVELOPMENT ON PAPER INSULATED CABLE.

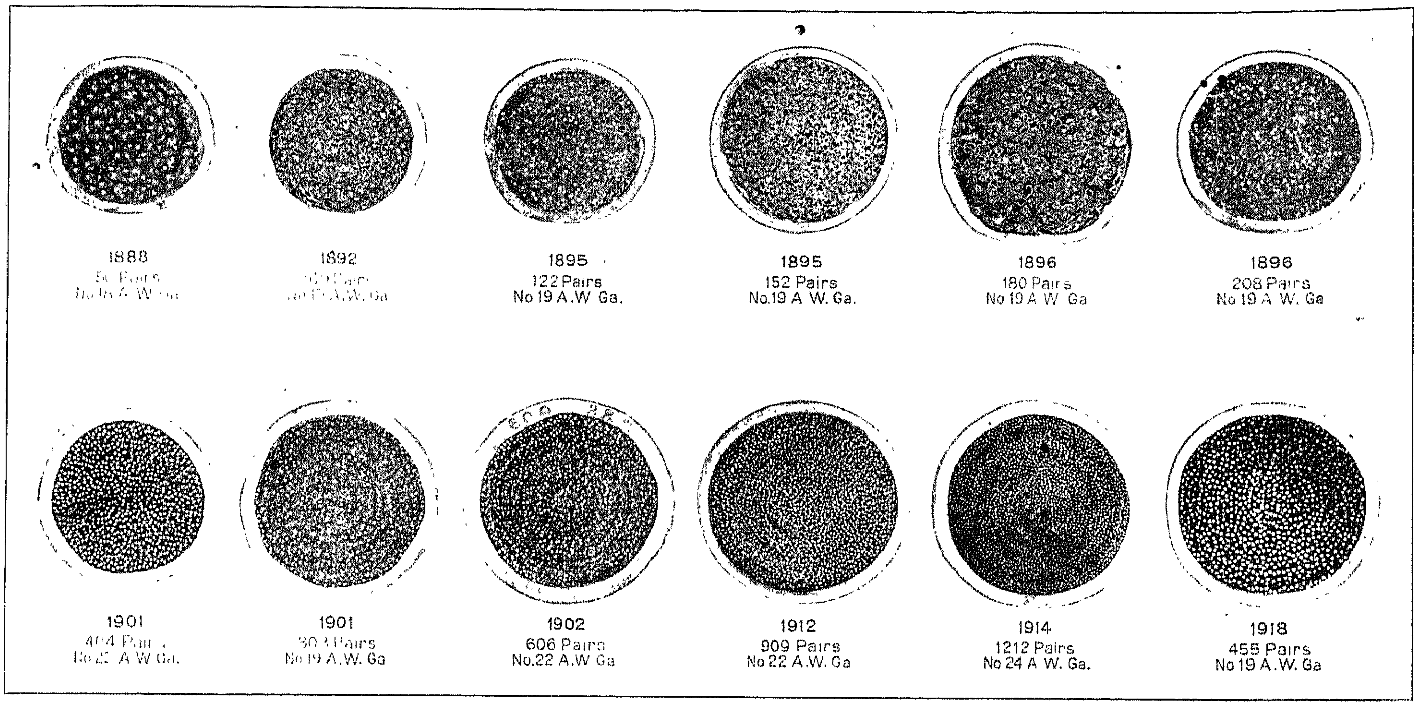


FIG. 5

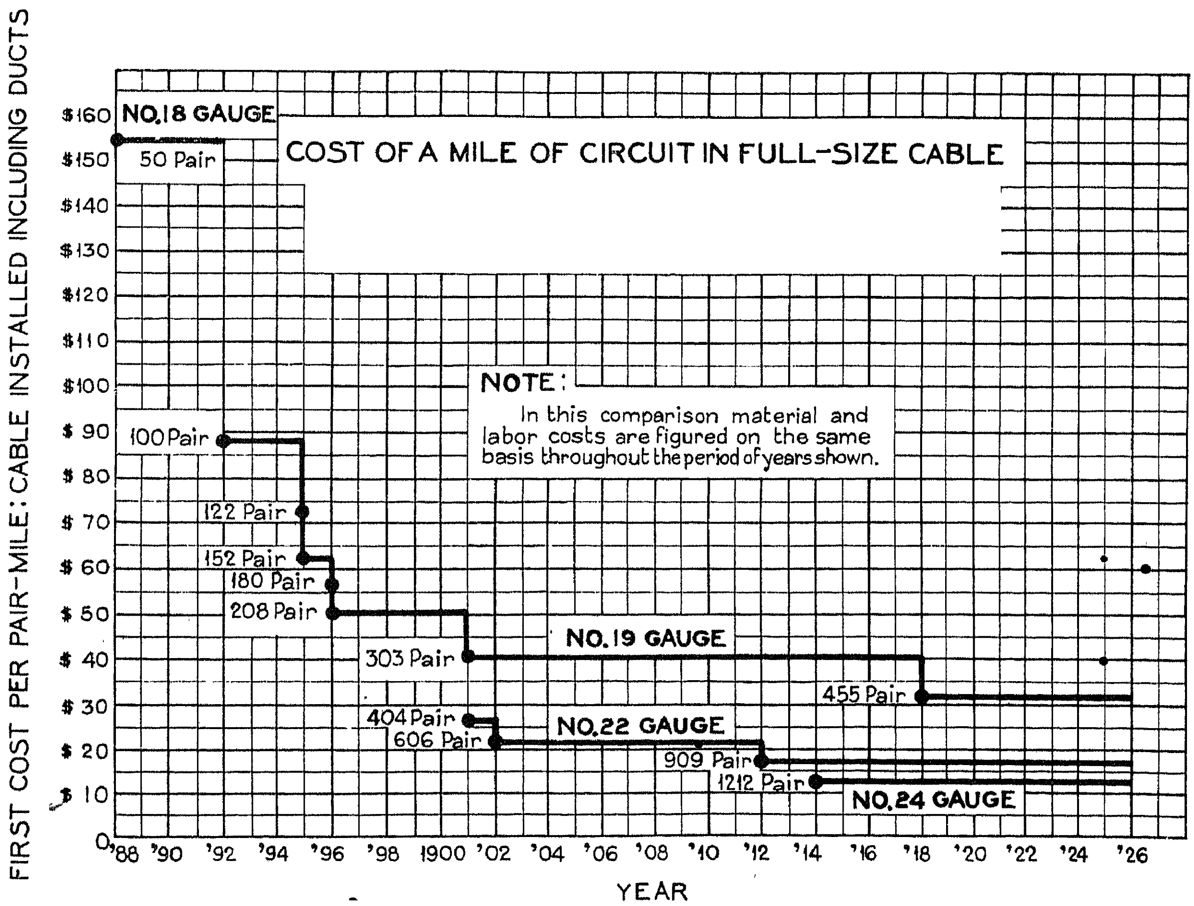


FIG. 6

finement in manufacturing processes required for quadded cables.

The discussion so far has been confined mainly to cable intended for local service, that is, cable providing

TABLE I

A. W. G.	Standard sizes—pairs	Average a-c. capacitance guarantee m. f. per mile	Principle uses
13	11 to 76	.071	Toll entrance and long trunks.
16	11 " 152	.071	
19	6 " 455	.090	Trunks and long subscriber lines.
22	11 " 909	.089	Subscriber lines
24	11 " 1212	.085	Short subscriber lines.

conductors to connect subscribers directly with the central office and different offices with one another. Gradually, the network of long lines connecting different exchange areas or cities grew and while the early lines were mostly open-wire lines, it was necessary to provide cable in and near the larger cities to bring these lines into the central offices. Most of the long lines were operated on the phantom principle where four wires are combined to provide two ordinary pair circuits and a third or phantom circuit which uses the four wires simultaneously. It was, therefore, necessary to provide cable for these toll entrances which could also be operated on the same phantom principle. More recently many long toll lines have been placed for their entire length in cables of this type.

One of the greatest difficulties in providing this type of cable was that of building it with sufficiently good electrical balance to avoid serious interference or "cross-talk" between the various circuits in the same four-wire group or "quad," such cross-talk being especially liable to occur because practically all of these lines are loaded. For a given degree of imperfection in capacitance balance, cross-talk is much more serious if the line is loaded than otherwise. A very considerable amount of work was necessary to determine the principles of design and manufacture which have the most influence in bringing about the best balance reasonably attainable.

The specified limiting degree of unbalance of the capacitance in quadded cable is indicated in Table II, and Fig. 7 is a diagram showing the capacitances involved and a brief explanation of them.

TABLE II

Capacitance in m. f. per mile		Capacitance unbalance in m. m. f. per 500 ft. length					
Pair	Quad	Side to side		Phanton to side		Phanton to phantom	
Av. .068	Av. .112	Av. 30	Max. 100	Av. 120	Max. 200	Av. 60	Max. 600

Diagram Showing the Capacities Involved in Capacity Unbalances between Circuits.

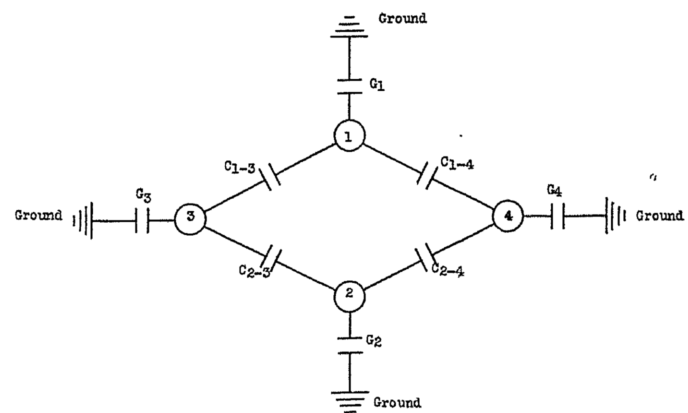


Fig. 7

***Class I Unbalances—Phantom to Side**

1, 2, 3, and 4 represent the four wires of a quad, of which 1 and 2 form one pair and 3 and 4 form the other pair.

Unbalance between Phantom and Side 1-2

$$= 2\,[C_{1\text{-}3} + C_{1\text{-}4} - (C_{2\text{-}3} + C_{2\text{-}4})] + G_1 - G_2$$

Unbalance between Phantom and Side 3-4

$$= 2\,[C_{1\text{-}3} + C_{2\text{-}3} - (C_{1\text{-}4} + C_{2\text{-}4})] + G_3 - G_4$$

Class II Unbalances—Side to Side

1, 2, 3, and 4 represent the same as in Class I Unbalances.

Unbalance between Side 1-2 and Side 3-4

$$= C_{1\text{-}4} + C_{2\text{-}3} - (C_{1\text{-}3} + C_{2\text{-}4})$$

Class III Unbalances—Between Circuits in Different Quads

Unbalances between two phantoms, or between pairs not in same quad or between a phantom and a pair not in same quad, in each case $= C_{1\text{-}4} + C_{2\text{-}3} - (C_{1\text{-}3} + C_{2\text{-}4})$ in which, for

(a) **Phantom to Phantom,** 1 represents the two wires connected in parallel of one pair of a quad, 2 represents the two wires in parallel of the other pair of the quad, and 3 and 4 represent similarly the pairs of another quad.

(b) **Pair to Pair,** 1 and 2 represent the two wires of a pair and 3 and 4, the two wires of another pair not in the same quad.

(c) **Phantom to Pair,** 1 and 2 represent a phantom as in (a) and 3 and 4 a pair as in (b).

The type of quad now most commonly used in toll cables in this country is known as the multiple twin type and consists when completed of two twisted pairs which are again twisted around each other. Differently colored wrappings of cotton around the several pairs hold the two wires of the pair together and afford means of identifying various types of quad and pair as used, for example, in the segregation of the circuits operating in different directions in the so-called four-wire circuits.

A type of quad construction different from that described above and commonly known as the "spiral four" type of quad has been used more extensively abroad than here. In this construction four wires are twisted together in such a way that at every position each

*Capacitance Unbalances involve differences of Direct Capacitances. See G. A. Campbell, *Bell System Technical Journal*, July 1922.

wire occupies approximately a corner of a square and the two diagonally opposite conductors are used to form a pair.

This construction has the merit of very low mutual capacitance of the pairs, but the disadvantage of very high mutual capacitance of the phantom. It has also been found more difficult with this construction to obtain sufficiently good balance to give satisfactory loaded phantom circuits. This type of quad has, therefore, in some cases been used without utilizing the phantom circuits. The loss of these phantom circuits is less than it might seem at first sight because, on account of the inherently lower pair capacitance for a given space per pair, more wires can be placed in the same space for a given capacitance than with other types of construction.

Another characteristic which under certain conditions is important is the alternating current conductance or leakance. The leakance which is measured in micromhos is that property which determines, under given conditions of potential and frequency, the losses in the insulation. These losses become of greater importance when the cable is loaded than when non-loaded and also of relatively greater importance when the conductors are large because then the dielectric losses become relatively greater in comparison with the lower losses in the decreased resistance of the conductor. For this reason many of the large gage loaded toll cables are treated with a special drying process to diminish the leakance.

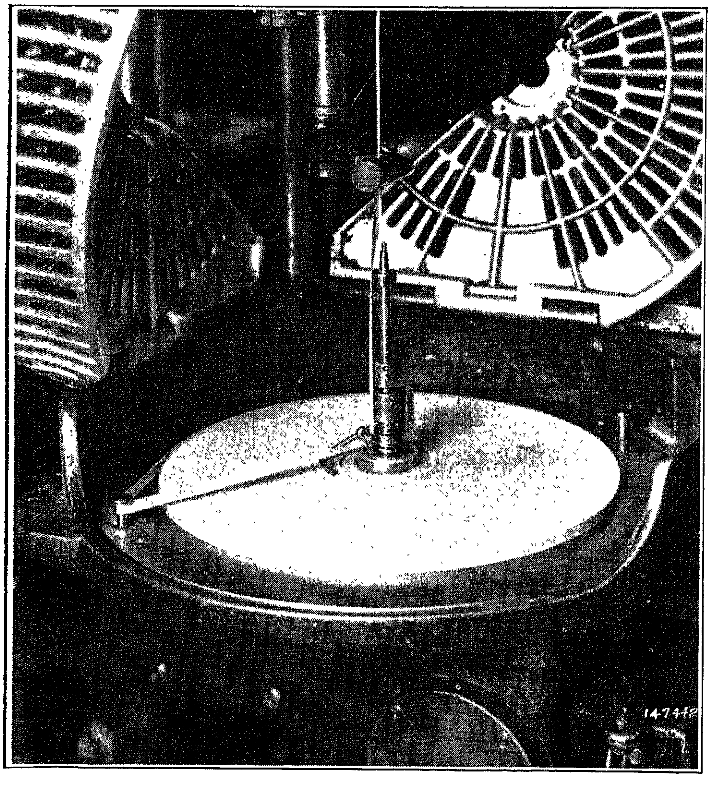


Fig. 8—Paper Insulating Head

Either quadded or non-quadded cable may be used on occasion for crossing rivers, bays, etc., and in these cases the lead covered cable is protected by being first served with two or three layers of jute roving impregnated with tar, then wound with galvanized steel armor wire, and again served with jute yarn, impregnated with an asphalt compound, although in many cases at present this outer serving of yarn is omitted. In case of injury causing an opening in the sheath of such a cable, water may enter the interior and interrupt the service. It is also liable to penetrate for a considerable distance and thus ruin a substantial length of cable which it then becomes necessary to replace. To diminish the amount of cable damaged in this way, this type of cable is sometimes made with a very large amount of paper insulation crowded into a small space to make the cable within the lead pipe very dense. The swelling of this paper as it becomes wet tends to retard the penetration of water and to diminish the amount of cable damaged.

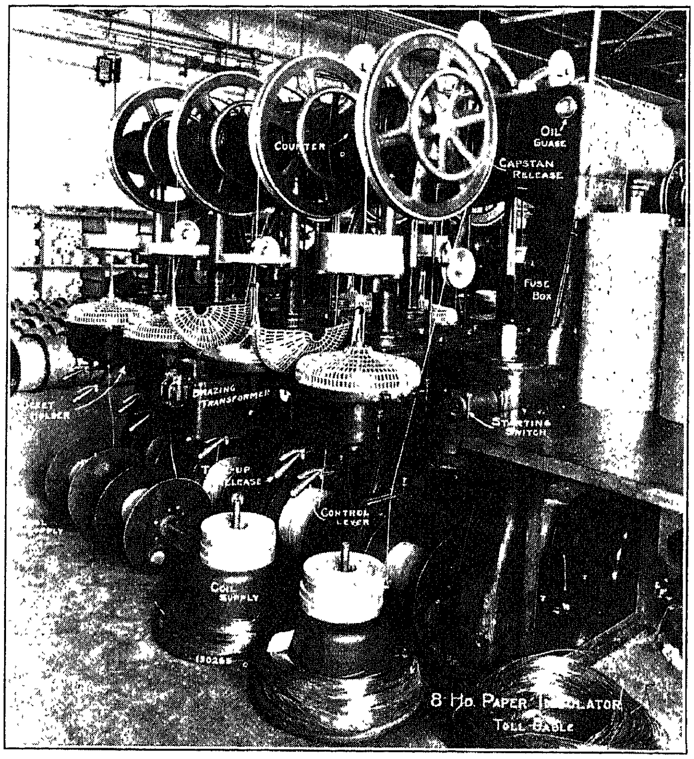


Fig. 9—Heavy Wire Insulator

This dense core construction has, however, the objection that it tends to produce circuits of lower transmission efficiency on account of the higher capacitance and leakance obtained. For this reason cables for this purpose in many cases are made with less dense core construction similar to that used in land cables but with the core treated so as to provide water barriers at frequent intervals to prevent or greatly diminish the passage of water through the barrier, commonly known as a "plug," so that the damage resulting from an injury to the sheath is substantially confined to the portion between two consecutive plugs.

One of the outstanding developments in cable manu-

facture which occurred about 1911 was the substitution of 1 per cent antimony in lead cable sheath for 3 per cent tin. The use of tin alloyed with lead for cable sheath had been instituted many years before, as it had been found that such sheath was more durable than sheath composed of lead alone and had better mechanical characteristics.

Exhaustive tests showed that lead antimony alloy sheath is equal in quality to lead-tin alloy and, although its use required the development of improved methods of mixing and extrusion, it has resulted in large cost savings.

Another decided improvement introduced later was the substitution of vacuum drying ovens for the old gas or steam heated air ovens. It was found that the drying time using vacuum ovens was reduced to about one-third as compared with hot air ovens together with improved quality and large cost savings.

Before the war the average demand for telephone cable in this country amounted to about 200,000,000 conductor ft. per week. During and after the war this demand steadily increased until now it amounts to about 600,000,000 conductor ft. per week or about 30,000,000,000 ft. per year, requiring annually

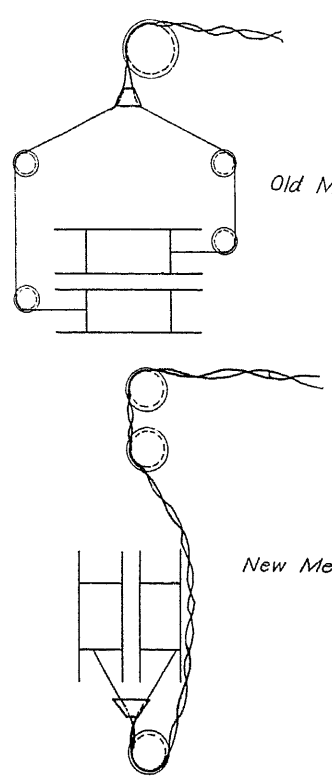


FIG. 10—SCHEMATICS OF OLD AND NEW TYPE TWISTERS

40,000 tons of copper wire, 75,000 tons of lead, and 6000 tons of insulating paper.

In planning for the manufacture of this quantity of cable, the design of all machinery was reviewed and changes made wherever possible to improve quality or increase output.

A great deal of work was done in improvement of insulating machines, and a ten-head vertical type insulator was developed to replace the older five-head horizontal type for non-quadded light gage wire. In designing the new machine many improvements were incorporated. The old machines had been built to

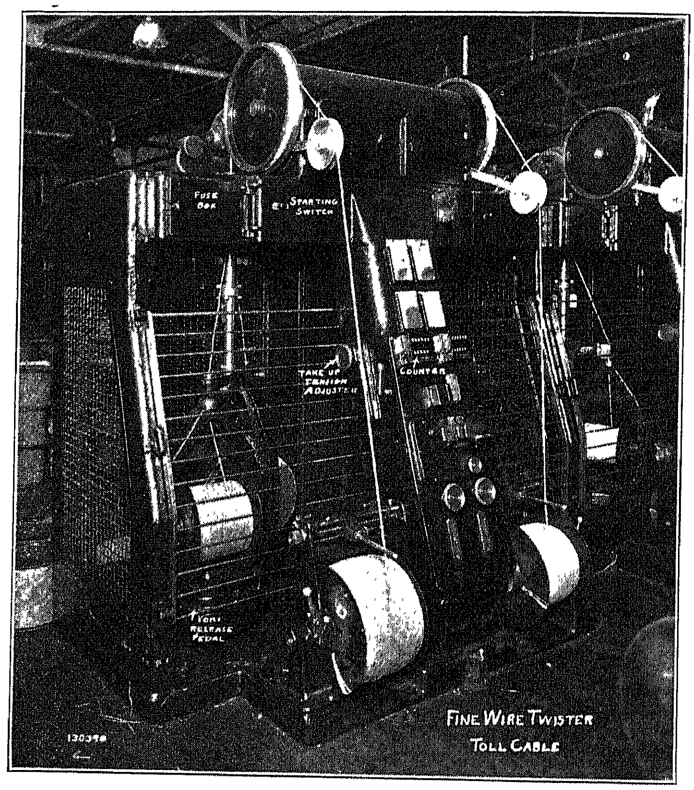


FIG. 11—COMBINED TWISTING AND QUADDING MACHINE

handle relatively strong paper and heavy wires and studies indicated that to insulate finer wires successfully with lighter paper, also to run at high speeds without stretching the wire, and apply a uniform wrapping without backlapping or folding over of the paper and with low breakage per pad the insulators should be rigid, the tension on the wires should be uniform, and both supply and take-up mechanisms should operate smoothly.

The relative floor space per head for the 10-head machine including operator's space is about 60 per cent of that taken by the five-head machine but based on production the relative space per unit of production is about 50 per cent. The new machine runs at a head speed of about 3000 rev. per min., carries a 12 in. pad of paper, and in general is a very substantial machine.

The insulating head, the vital part of the insulating machine, has undergone many changes to accommodate the thinner, narrower insulating papers. One of the most important of these has been to improve the tension mechanism which now consists of a very small multiple disk clutch actuated by a system of levers so that a very light but very uniform tension is applied at all times.

This is not only making possible the use of smaller paper ribbon but may permit of changes in the composition of the paper with resultant cost savings. This head is shown in Fig. 8.

Another desirable feature in a paper insulating machine is a bare wire detector as the insulation sometimes parts after passing through the sizing die or polisher as it is called, separates for a few inches and then picks up and goes on. Many electrical devices have been tried and practically all have the objection of high maintenance cost. A very simple and effective remedy was the installation of a second polisher placed between the capstan and take-up spool which catches broken paper and pushes it back until the operator sees and repairs it.

The insulating machine used for heavy gage wire is an 8-head machine built along the same general lines

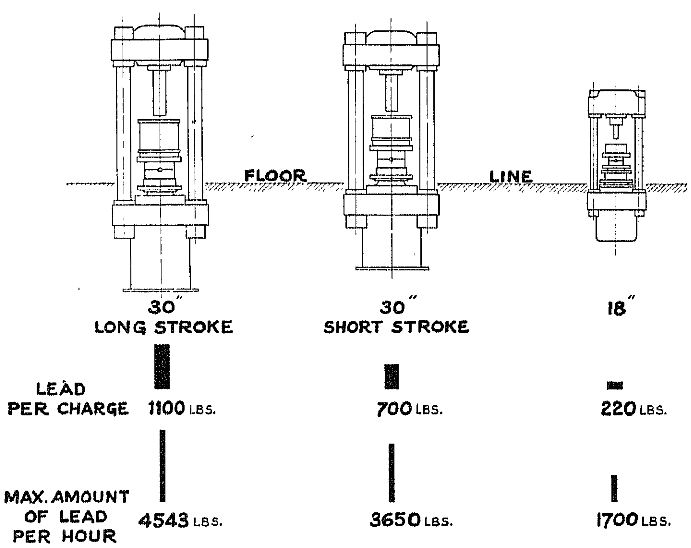


FIG. 12—SCHEMATIC SHOWING RELATIVE INCREASE IN SIZE OF LEAD PRESSES

as the 10-head machine. This is illustrated in Fig. 9.

The method of splicing the copper wire is by means of a transformer, the low-voltage side of which is equipped with clamps for holding the two ends of wire which are butted together, heated by electric current, and brazed by the application of borax flux and silver alloy solder. The transformer windings are so designed with low internal resistance that, although different sizes of wire may be handled, the resistance of the wire between the clamps is so large in proportion to the total resistance that it automatically controls the current and prevents overheating of the wire.

Splices in the insulating paper are made by the application of a thin strip of gummed paper.

New twisting machines for non-quadded light gage wire have been developed and these machines have some unique features which are worth a word of explanation. Fig. 10 shows schematically the old type of twister used ten years ago in which the two spools were placed with axes vertical inside of a flier which carried guide bushings through which the wire from the two spools was brought up to the center of the yoke and to the capstan. These machines operated at 500 rev. per min.

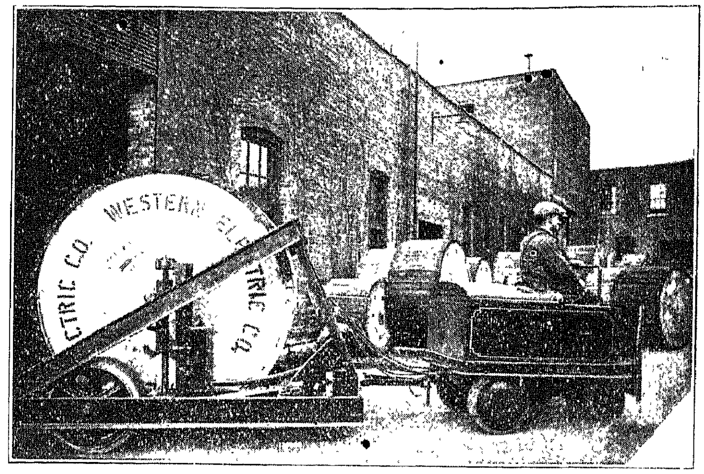


FIG. 13—ELECTRIC TRACTOR AND TRAILER FOR HANDLING CABLE REELS

and produced one twist per revolution. Assuming a 3 in. twist, the output would be about 125 ft. per min. In the new machines the spools are mounted side by side in a flier, the spools not revolving around each other, with axes horizontal and the wire from each is taken off in a downward direction around a guide pulley and then up through the flier, around another guide pulley and to the capstan. With this arrangement two twists per revolution of the flier are produced and, as the machine is built to operate at 1000 rev. per min., the output for double the speed of the old machine is four times as great or about 500 ft. per min. for a 3 in. twist. Additional features are special tension devices to insure uniform tension on the wire and supports to assist in loading spools of wire into the yoke.

The twister for pairing and quadding heavy gage wire in one operation is shown in Fig. 11.

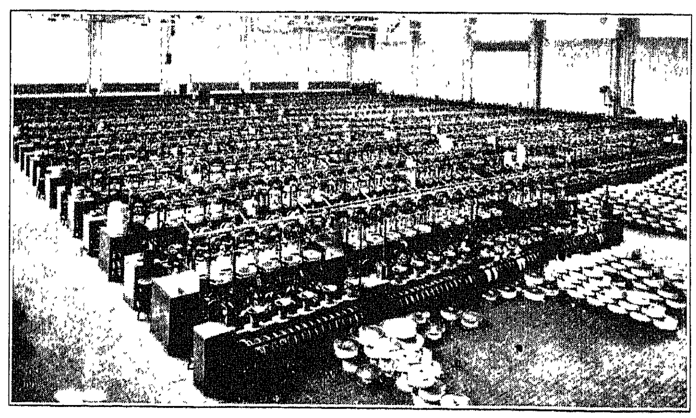


FIG. 14—INSULATING MACHINES

Each spool, containing two conductors, is mounted in a yoke which revolves on its own axis to give the pair twist and the two yokes revolve around each other to give the quad twist. This is accomplished by an

arrangement of change gears from which can be obtained practically any length or direction of twist desired.

Modern stranders follow the same general line as the older stranders but the whole design has been reviewed in detail with the view of strengthening and perfecting, and improved tension devices have been developed consisting of a tension arm actuated by the pair which in turn applies a brake to or removes it from the reel head. These are adjusted to give a tension of about three pounds per pair which causes no stretch and prevents over-running. With these, it is possible to run very fine wires at a minimum tension with a maximum smoothness of operation. The drums are gear driven and are capable of running up to 100 rev. per min.

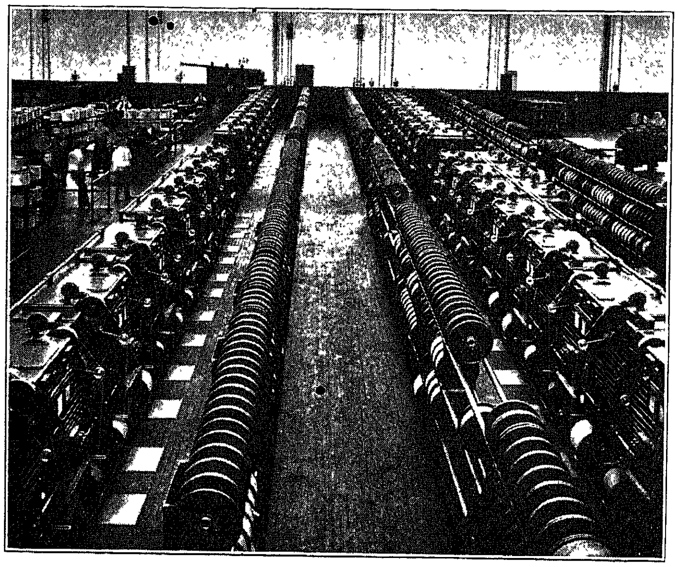


Fig. 15—Twisting Machines

After the cores are stranded, they are dried under vacuum to remove the moisture from the paper and then covered with a lead alloy sheath.

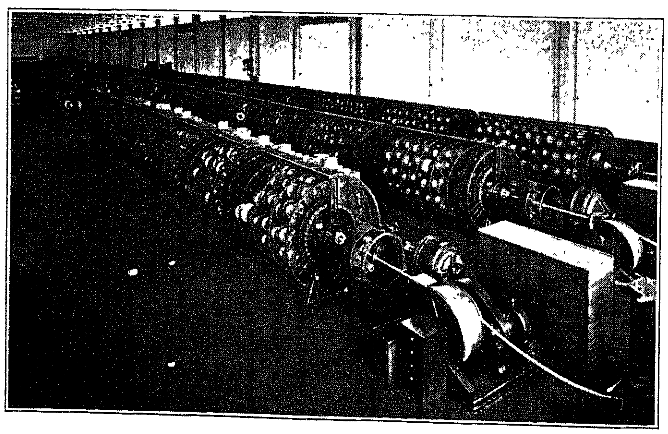


Fig. 16—Stranding Machines

It is necessary after the cable is removed from the vacuum drier to keep it in an atmosphere of a low moisture content until the lead sheath is applied. This was formerly accomplished by placing it in an oven at a temperature of about 160 to 180 deg. fahr. with a resultant relative humidity of not over 10 per cent. Cables maintained at this humidity would pick up very little moisture but in transit from the vacuum drier to the storage oven some moisture might be absorbed; also working in and out of these hot ovens was not particularly pleasant. Therefore, a method was developed for installing the vacuum driers in such a way that one end opens into an enclosed storage area in which the air is maintained at a temperature of about 100 deg. fahr. and a relative humidity of less than 10 per cent until the cables are covered with lead. This temperature and humidity are obtained by cooling the incoming air to a dew point corresponding to the temperature and relative humidity desired and then passing it into the oven. A considerable engineering problem was involved in determining the heat given off by the vacuum driers and the hot cables and the additional moisture introduced by infiltration through walls, doors, etc.; also the relation between relative humidity, moisture content of paper, and electrical characteristics presented a most interesting field for study.

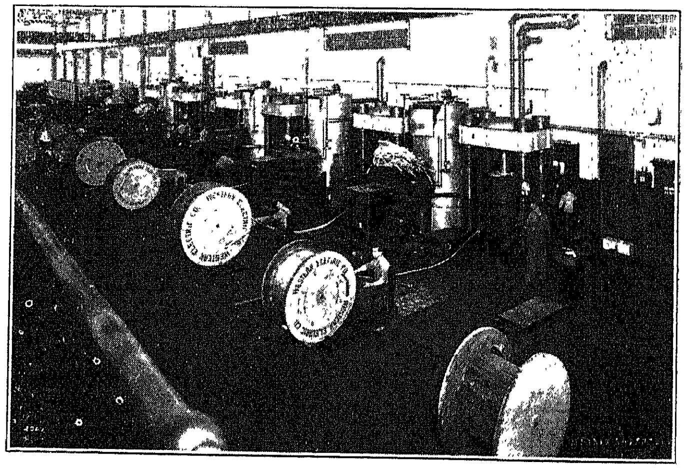


Fig. 17—Lead Press Equipment

The method outlined above has proved very satisfactory as the cables do not absorb enough moisture to affect their electrical properties and the conditions in the storage area are not unpleasant; in fact, during the summer they are somewhat more agreeable than the outside air during periods of high humidity.

The process of applying lead sheath to cable is one which has not undergone any change in principle since sheath was first applied directly to the cable instead of cable being pulled into it. There has been, however, a number of developments tending to improve the quality or increase the output.

In covering a large cable something more than half of the total time of one cycle of operation is taken up by filling the cylinder with lead and cooling under pressure to the point where it can be extruded. The tendency,

therefore, has been to build presses with larger lead containers in order to increase the time of extrusion relative to the total cycles.

The diagram (Fig. 12) shows schematically an early

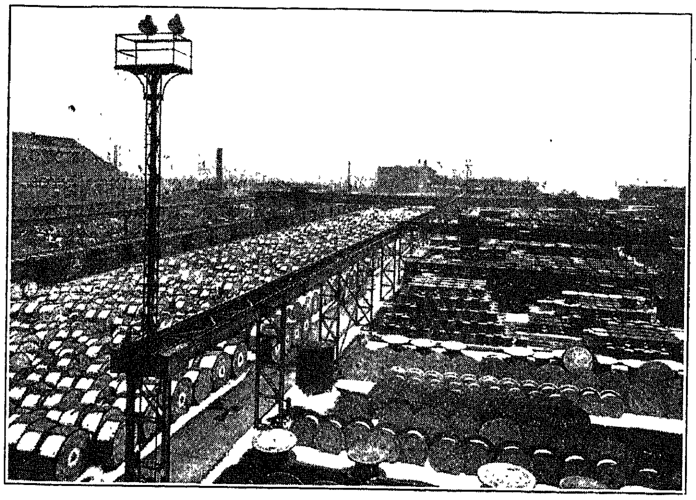


FIG. 18—GENERAL VIEW OF REEL YARDS

type of press, one which was considered standard a few years ago, and one of the presses designed and built recently. Underneath each press is a figure showing the lead content per charge and the relative amount of lead extruded per hour by each of the three presses.

As will have been noted from the diagram, the stroke of the newest type of presses is about one foot longer than that of the former presses although the diameter of the lead container and the diameter of the water ram are the same.

The pressure for operating these presses is furnished by a hydraulic pump, pumping water at six thousand

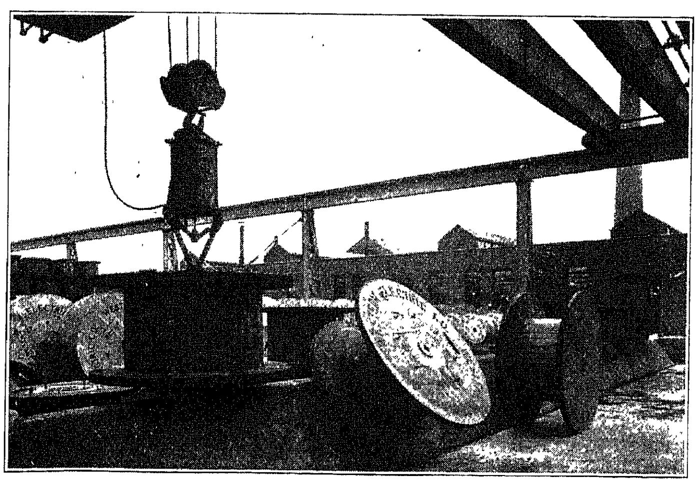


FIG. 19—DELIVERY OF EMPTY REELS FROM YARD

lbs. pressure per sq. in. Presses were formerly connected to four plunger vertical type pumps, but it was found that more water could be used with the large sizes of cable and, therefore, new pumps were built with six plungers, giving a proportionally greater output.

The diameter of the lead ram is one-third that of the water ram so the pressure on the lead during extrusion is about 54,000 lbs. per sq. in.

Aside from increasing output many studies have been made to determine the exact mechanism of lead extrusion, the relative flow of lead in different parts of the extrusion block, the effect of application of heat at different points, etc.

An interesting experiment consisted in filling an extrusion block, with layers of different colored waxes and noting their flow under pressure. This gave valuable data as to the proper contour of the extrusion chamber.

The concentricity of sheath is affected not only by the contour of the extrusion chamber but also by the manner in which heat is applied; and thickness is

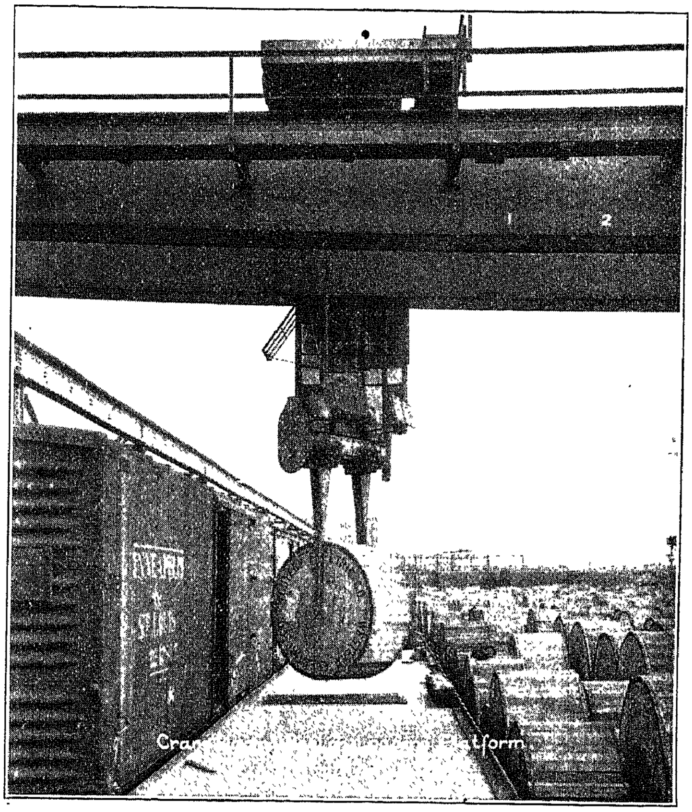


FIG. 20—CRANE PLACING REELS ON LOADING PLATFORM

affected by temperature and speed of extrusion so that the human element is an important factor, and it is necessary to have thoroughly trained and reliable operators on this kind of work. Temperature indicators are used to show die block temperatures and the temperature of the molten lead is automatically controlled and recorded.

Handling of lead-covered cable on reels, the total weight of which runs from one to five tons, is a very distinct problem. This handling from press to test is done by a crane which picks up the reels and carries them to the place where they are to be tested for insulation resistance, capacitance, dielectric strength, etc.

After the cables are tested, the ends are sealed and

wooden lags are fastened around the periphery of the reels after which the cables are taken to a storage yard until the customer's order is completed at which time they are shipped. A special tractor and trailer, Fig. 13, has been developed and substituted for manual handling.

Handling cables from the reel yard to the loading platform was a very serious problem particularly in the winter during snow storms. This was taken care of by the installation of overhead cranes for picking up reels and placing them on the platform.

The lifting mechanism for empty reels consists of a solenoid operated plunger controlled by the crane operator. The reels are turned on the side, the plunger inserted in the bushing and the operation of the solenoid throws out two lugs which prevent the plunger from being withdrawn, and lift the reel. When the reel is to be released, it is put down on an inclined surface which turns it back on to its flanges. This method of lifting empty reels permits them to be stacked one on top of the other and saves storage space.

The lifting mechanism for full reels consists of two side arms with lugs, moved horizontally by means of a double-threaded screw and a motor controlled by the crane operator. With this device the crane operator can pick up and put down any reel without the assistance of a ground man.

Figs. 14 to 20 show insulating, twisting, and stranding machinery, lead presses, and cable reel yard with cranes and special lifting equipment for both empty and full reels.

The methods of cable manufacture are ever changing. What has been described as strictly up to date today will, doubtless, on account of new developments be superseded by new methods, new equipment, and new designs so that the cable plant of the future will be different from and more efficient than that of the present.

Discussion

E. O. Neubauer: Mr. Hart, in his paper, has called attention to the progress in the manufacture of non-quad cable. The large increase in the number of pairs placed in a single sheath was due in part to improved manufacturing methods, but was largely due to a gradual decrease in the size of conductors and the thickness of the in ulation used. This resulted in the manufacture of cables having considerably higher transmission equivalents than the early cables which were mostly large gage. The transmission equivalent of a 26-gage cable, for example, is about 1½ transmission units higher than that of an 18-gage circuit.

The non-quad cables are used mostly for exchange distribution, that is, to connect subscribers' stations with the central office and to connect central office and office exchanges. The increased transmission losses were necessarily met by improvements in developments in other parts of the telephone plant. In the case of subscribers' lines, the increased transmission losses were met by improvements in the transmitter, receiver, and induction coil of the telephone, so that today a 24-gage circuit with the improved instruments will give as good transmission as an 18-gage circuit with the instruments formerly in use.

One of the diagrams of Mr. Hart showed the gradual decrease in the cost per pair of cable between 1888 and the present time.

One of the most important items in the cost of outside plant facilities is conduit. In Chicago the cost of conduit is about $4000 per duct including a proportional part of the associated manholes. This one item alone is considerable when it is remembered that in 1888, 36 ducts were necessary to serve the number of subscribers served today with one duct.

The introduction of loading has made possible the use of small-gage cables to connect two offices in an exchange area. A trunk connecting two offices, say 20 mi. apart, could employ 22-gage conductors properly loaded whereas if the loading were not available it would be necessary to use 16-gage conductors which would reduce the number of pairs available from 900 to 150.

Quadded cables are manufactured in the so-called large gages, that is, the 13-, 16-, and 19-gage conductors and the insulation is somewhat heavier than in the smaller gages. The wires are also placed more loosely within the sheath. The result is that the transmission equivalents obtained with quadded conductors are somewhat better than with non-quadded conductors. The reason for this is that quadded cables are used for toll service mostly, which means that they have longer distances to span than the non-quadded cables. This makes it necessary to obtain cables of a smaller transmission equivalent per mile than the non-quadded cables. Even with the use of larger gages it is also necessary to employ amplifiers where the length of circuit exceeds about 80 mi.

H. P. Charlesworth: Possibly a few operating considerations might be of interest.

When we consider that today we are requiring for the telephone companies of the Bell system, more than 30,000,000,000 conductor-ft. of telephone cable each year we see how important these various developments which have been discussed really are in the daily operation. The fact that we can now get 1200 and 1800 pairs of wires in these cables is interesting because it is hard to realize how we could possibly serve our large communities without developments of this kind permitting us to get a large number of wires into a building. Again, without this large number of wires in a single sheath our streets in the downtown sections would be pretty well occupied with nothing but telephone conduit, and of course space must be provided for the electric, steam, gas, and all the other utilities as well. That further illustrates the importance of these developments.

Another interesting matter might well be mentioned relative to the toll-cable problem. That program and the extension of toll cables has gone on throughout the country in the last few years on a very large scale. Today we have an all-cable route all the way from Boston through to St. Louis with various branches bringing in a very large number of cities on a cable basis.

These cables require, as one of the speakers mentioned, amplifiers at about every 50 mi. for the longer lines and the circuits are operated for those long distances on what is called a four-wire basis. That is, the voice coming from New York to Chicago goes on one pair of 19-gage conductors and back on another pair with amplifiers in each of the circuits. That permits a more stable and more satisfactory operating circuit. Then at the terminals these pairs are brought together, of course, into the usual two-wire circuits to permit of connection through the switchboard to the ordinary subscriber's line. The loss, to start with, is of course enormous and the amplification has to be perfectly enormous, something like 10^{45} to make up for the enormous loss and to give a margin for satisfactory transmission.

Under those circumstances a relatively very small change in the temperature conditions of cable, whether in the aerial or

underground portions, would have a very definite and very decided effect on the attenuation so that it is necessary to regulate that, and this is accomplished by means of having a pilot wire, so-called, in the cable associated with certain automatic control apparatus so that as the wire changes in temperature you have automatic regulation of various amplifiers along the cable thus maintaining a stable and definite net over-all efficiency.

The cable program is extending now up toward Minneapolis and before long will be down toward Atlanta in the South, up and down the Pacific Coast in certain sections, particularly between San Francisco and Los Angeles. A second route has already been provided from the East around through Buffalo meeting the other cable at Cleveland.

C. D. Hart: The only thought I should like to add is that the discussion has tended to make apparent the need for great care in manufacturing cables, particularly loaded cables, and has broadened the picture to include not only the manufacture of cable but its place in the general communications plan.

Telephone Toll Plant in the Chicago Region

BY BURKE SMITH[1] and G. B. WEST[2]

Associate, A. I. E. E. Non-member

***Synopsis.**—This paper described the telephone toll system in the region within a radius of about 50 mi. from Chicago. In this system have been established 21 toll centers at which are handled the toll traffic of their own exchanges and 95 other exchanges in the area. Descriptions are given of the toll plan and the toll plant, methods of handling toll calls, volume of traffic handled, etc. A most important consideration is the very rapid growth taking place in toll-service requirements in this region.*

COOK County and its seven adjacent counties in Illinois, and two in Indiana, together form the metropolitan area which is referred to in this paper as the "Chicago Region." Within this area there are about three and one-quarter million people in Chicago proper, with another one and one-quarter million distributed in about one hundred communities in proportionately decreasing densities from the Chicago city limits to the outer boundaries about fifty miles distant. The growth of the population in this area is at the rate of approximately a million per decade.

This area is served telephonically through local exchanges which are, for the most part, identical with the one hundred odd communities already referred to, and each receives service within its area under its local service tariffs. Between any one community and any other community, service is, in general, subject to an additional tariff or toll charge based on the center to center distance.

The general advancement of this region has been material. This has been more than reflected in the accompanying increase in telephone business. Within this business the rapidity of increase has been even more marked in the toll than in the local phase. Since all indications point to a continuance in this same relative progress, it may be appreciated that the toll development will present a continuing problem if no other factor than magnitude alone need be considered. Along with magnitude, however, there are problems of re-alinements of distribution as communities of interest and methods of operation change and plant design advances.

It is obviously as impractical to provide each local exchange with direct or fixed connections to every other exchange as it is to so deal with the various subscribers' stations within a local exchange. Switching or distribution centers must, therefore, be arranged which result in greater toll plant efficiencies and toll line route concentrations. The actual result of this in the Chicago region has been the establishment of 21 toll centers, at which are handled the toll traffic of their own exchanges and the other 95 exchanges in the area. These 95 exchanges have therefore become, for toll purposes, satellites to these centers, or as it is generally expressed, "tributary exchanges." It is expected that these 21 centers may be still further reduced with improvements in methods and plant design.

Toll traffic between these toll centers, whether originating at the centers or at their tributaries, is handled by one of three operating methods known respectively as:

1. *The Toll Board Method,* in which the calling subscriber is connected with the recording operator, familiarly known as "Toll" or "Long Distance." At the present time the recorder takes the details of the call and dismisses the subscriber until a line operator can complete the call. This method is now undergoing a change. As soon as equipment rearrangements are available the work of the recording and line operators will be combined and marked service improvement effected.

2. *Two-Number Toll Board Method,* in which the "A" operator accepts the call and passes it to a "Toll Board" operator, who handles the call while the calling subscriber remains at his telephone. This method will tend to merge with the improved toll board method.

3. *A-B Toll Method,* in which the "A" or subscriber's operator, on receiving a call from the subscriber, supervises the call through to the called station, the calling subscriber staying at the telephone.

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Presented at the Regional Meeting of District No. 5 of the A. I. E. E., Chicago, Ill., Nov. 28-29, 1927.

Under the last two methods, only calls made for a station by number can be completed, and the first method is used for all calls on which a particular person is asked for. The determination of the proper use of each of these three methods involves consideration of service requirements and economies. In general, the so-called A-B method is used for short-haul traffic of large volume, the two-number toll board method for short and intermediate distances of lesser volume, and the toll board method for long-haul traffic of small volume. These, of course, are only general groupings, and the method adopted in any individual case is based on the actual conditions to be met.

There are also, of course, variations within these methods, such as, for example, the use of a tandem switching center in an A-B method. This variation as applied to Chicago, consists of a tandem board at which are centered toll trunks from Chicago exchanges as well as from outlying exchanges. Calls received by the "A" operator at a Chicago exchange, for one of these outlying exchanges, may be routed via the tandem switching operator, who in turn connects through to the called office, via the toll trunks available to her. In this way it is not necessary to have direct toll lines from every local board in the area to every other local board; yet, at the same time, it is possible to complete these calls by the A-B method. There is at present only one tandem board in the Chicago region, and this is located in the loop district. Of course, as the volume of traffic between any two exchanges, which is handled through the tandem board, increases sufficiently to make it economical, direct toll circuits between the two exchanges are provided.

Progress in the Chicago region has been steadily changing from a condition of practically all toll board operation with the hang-up method, to two-number and A-B toll methods without hang-up as the toll volumes have increased and station-to-station service has become more popular until today fully 87 per cent of the Chicago regional toll traffic is handled by the A-B method. The improved toll board method will further increase the percentage of business handled on a "no hang-up" basis.

In this connection, it should be noted that concurrently with this change from toll board to A-B operation has come a marked change in speed of service. The average speed of service, that is, the average time from the request for a number by the calling subscriber to the ringing of the bell of the called subscriber, under the toll board method, averaged about seven min., while the speed of service under the two-number and A-B methods averages less than one min. Part of this reduction in time of connection is, of course, a direct result of the methods of operation, although part of it is also a result of the more liberal provision of facilities. However, such provision to permit of faster service has resulted in stimulating the use of the toll service, with a corresponding increase in the size of circuit groups and in the efficiency and speed with which these circuit groups can handle the traffic.

Associated with this regional toll traffic, there is the traffic which goes out of the area to more distant points, and that which comes into the area from distant points including traffic to and from such points which must be switched at a center, like Chicago. The economical provision of the plant to care for this extra regional traffic, with that for the short-haul traffic, further adds to the complexity of the plant design.

The provision of the plant for this intra- and extra-regional traffic to be economically carried out must be based on some general plan of future development within the area. Such a plan, generally known as the "toll fundamental plan," projects volumes of traffic, anticipates methods of handling, and arranges toll centering, tributary, and route layouts for some ultimate period, normally about 20 years in advance. Such

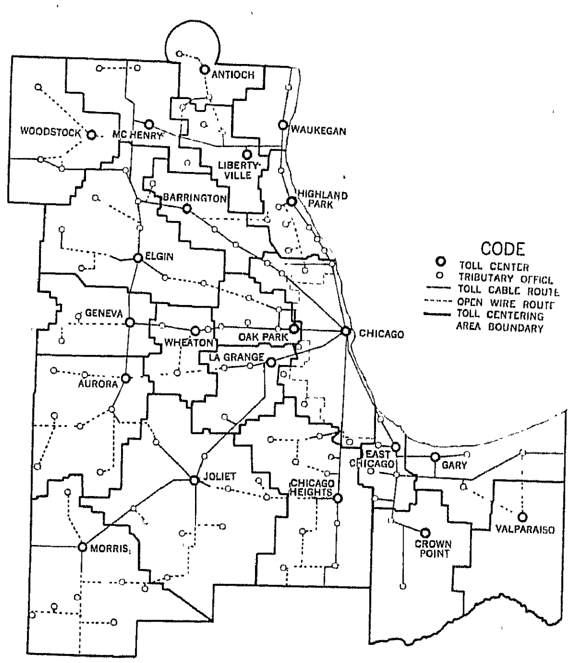

FIG. 1—TOLL FUNDAMENTAL PLAN

a plan must, of necessity, be reviewed and revised from time to time to keep pace with the developments and changes in toll service requirements, and is a guide to current toll plant construction rather than an absolute control of it.

Illustrations of some of the problems of growth and development of toll plant within the Chicago region follow:

Referring first to the toll fundamental plan, Fig. 1 shows the grouping of the exchanges in the Chicago region around the toll centers. For example, the small exchanges around Joliet under this plan reach Chicago and other points via Joliet. This figure incidentally indicates the several toll routes radiating from Chicago, such as the route along the North Shore, that northwest from Chicago toward Barrington, another directly west through Oak Park and Geneva,

and the one southwest toward Aurora with a branch toward Joliet and Morris; still another directly south to Chicago Heights, and one southeast to East Chicago which forms part of the main route to points East, including New York.

Considering now the growth in toll traffic in this region, there were ten years ago approximately 560,000 telephones with approximately 11,600,000 toll messages per year. In this same area, with something over

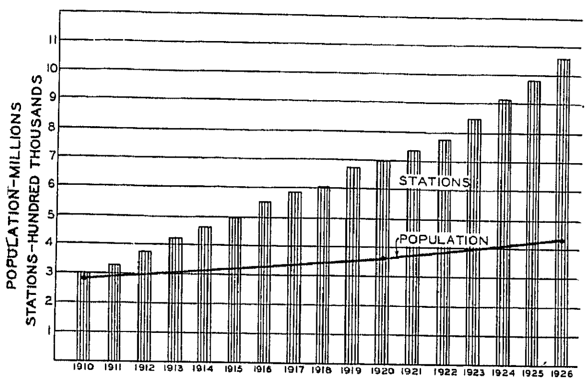

FIG. 2—TOTAL STATIONS AND POPULATION IN CHICAGO REGION

one-million telephones, we are now handling approximately 46,000,000 toll messages per year, or an increase of 300 per cent, while the number of telephones has increased only 90 per cent, and the population approximately 33 per cent. These relations are shown diagramatically in Figs. 2 and 3.

While a large part of this increase in toll traffic is within a 50-mi. radius of Chicago, yet the longer haul has increased greatly, as for example, between Chicago and St. Louis, 185 messages per day ten years ago, compared with 650 messages today; between Chicago and Detroit, 180 messages per day ten years ago compared with 1000 messages today.

Toll cable has been the solution of the increasing toll circuit requirements, since there is a definite limit to the number of circuits which can be provided by open wire.

Notwithstanding the continued use of open wire on the less dense routes, the extension of cable has decreased the toll open wire in the plant. This is shown in Fig. 5. It will be noted that cable wire mileage has increased from 36,000 in 1916 to 224,000 in 1926, an increase of 520 per cent in 10 years, while toll aerial wire mileage in this region has decreased somewhat during this period.

The rapid extension of the toll cable plant is shown in Fig. 4 on which is indicated the cable in service five years ago, the cable now in service, and that rather definitely foreseen within the next five years. It should be noted that in several of the routes shown a second cable, and in some cases a third and fourth cable, has been placed.

In designing such a cable network as this, there are a great many problems which must be solved before the plant can actually be provided; *e. g.*, starting out with an assumed grade of transmission, which it is necessary to provide from any station to any other station, the distribution of the losses must be economically apportioned. Take the simplest case of toll connection, consisting of a calling subscriber's loop, the called subscriber's loop, and the connecting toll circuit. Probably it would be possible to apportion 45 per cent of the loss to each subscriber's loop, and design the transmission of the toll circuit so that only the remaining 10 per cent would be in that portion of the connection. Or it would also probably be possible to assign 10 per cent of the loss to each subscriber's loop, and take up the remaining 80 per cent in the toll circuit. There is, of course, an economical division of these losses, and these must be determined in designing the toll plant.

Consider the design of the tandem trunk plant. These trunks may be classified into two groups, those connecting the tandem board with city offices, and those connecting the tandem board with suburban offices. If we should divide the total allowable line loss between these two groups equally, we would not obtain an economical balance, since the tandem trunk which is extended into suburban territory may be as much as fifty mi. in length, while the city tandem trunk will be very much shorter. There is, therefore, a very material

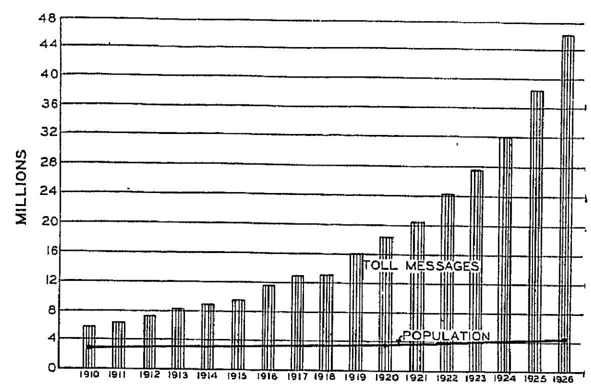

FIG. 3—TOTAL TOLL MESSAGES AND POPULATION IN CHICAGO REGION

saving by dividing the allowable losses unequally between these two classes of tandem trunks. In Chicago a study of the costs involved showed that this division of losses should be made up as follows:

Tandem trunks in the metropolitan zone (within the city limits principally) .... 5.0 Transmission units[3] allowable loss.

Tandem trunks within the suburban zone..........10.4 Transmission units allowable loss.

In the earlier days of the telephone business, all toll circuits of any appreciable length were provided by bare

3. For description see paper by W. H. Martin, A. I. E. E. TRANS., Vol. 43, 1924, p. 797.

wire strung on insulators, and it was not until a relatively few years ago that the development of the art permitted the use of cable circuits for this purpose. The earlier toll cables consisted simply of insulated wires, twisted in pairs. In this period transmission losses were so large that this type of cable could only be used for short distances, even though consisting of 13 and 10 gage wire.

The development of the loading coil, which has been described in other papers presented before the Institute,

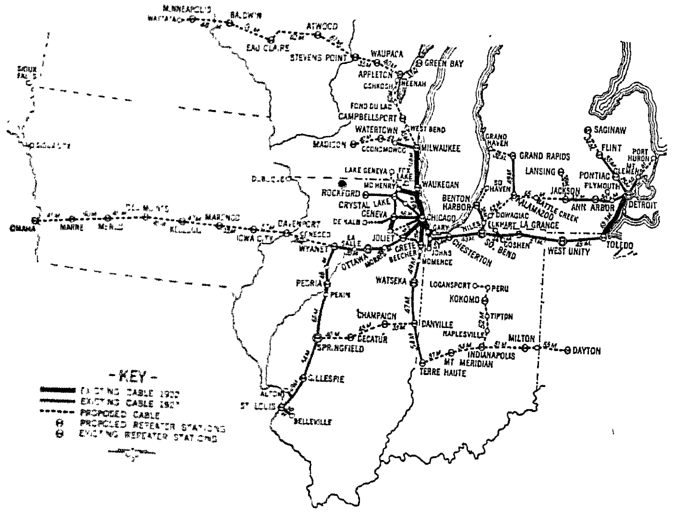

FIG. 4—TOLL CABLES IN THE GREAT LAKES DISTRICT

permitted further use of cable, and made cable available for increased length of haul where the volumes of traffic demanded additional facilities.

Since their introduction, the development of loading coils has advanced materially. The first coils introduced into the toll plant, some 25 years ago, were of iron core construction. While these coils were satisfactory under the conditions for which they were developed, when telephone repeaters became available it became desirable to provide improved types of loading coils. A loading coil having a pressed powdered iron core was, therefore, made available. The outstanding advantages of this coil was its higher magnetic stability and the smoother impedance conditions on the lines resulting from its use.

This coil has proven satisfactory for repeatered circuits. It is now being superseded for new construction, however, by a new type of coil having a pressed powdered permalloy core. This new core material permits a large reduction in the size of the coils without degrading established efficiency standards, and will result in large plant economies. Fig. 6 shows the relation of size of pots required to incase a given number of the new and old coils. This reduction in size is of great advantage where such coils must be placed in underground systems in congested city streets, or where in the country it is desirable to place them on pole fixtures.

Another development in the cable art is that of quadded cable. In this type of cable two pairs of wires, each constituting a circuit, are twisted together to form what is known as a "quad," and these quads may be used to provide a phantom circuit, thereby increasing the message capacity of the cable by 50 per cent. While this plan of making available a phantom circuit had previously been used in the open wire plant, it was not until quadded cable was developed that the phantom was available in cable circuits. The use of quadded cable for circuits using direct signaling, however, introduced another complication, in that the phantom circuit requires the introduction of a repeating coil at each end of each of the physical circuits, which will, of course, not permit direct-current signaling. It therefore becomes necessary in these cases to "by-pass" direct-current signaling around the windings of the phantom repeating coil, in order to make use of the phantom possibility. The economics of this form of signaling must be studied in each individual case.

Another important factor in the extension of cable for toll purposes is its immunity from storm damage. As is well known, open wire is subject to very serious breaks in the sleet storm area, while cable is practically immune from damage in such storms. It is estimated that to make an open wire line strong enough to give a strength of construction comparable to that obtained with aerial cable would require very large poles on very short spacing or other special construction. Such a

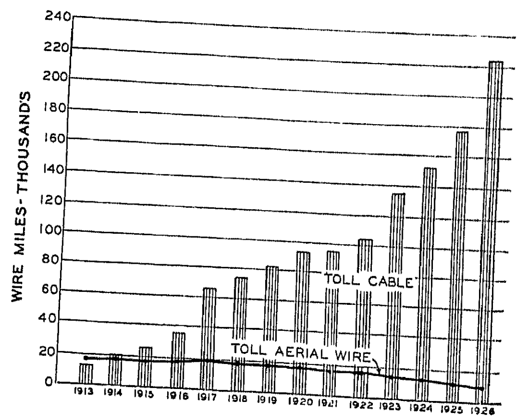

FIG. 5—TOLL CABLE WIRE AND AERIAL WIRE MILEAGE IN THE CHICAGO REGION

line also would need at least No. 8 B.W.G. hard-drawn copper wires. It is not certain that even such a line would stand up under severe storm conditions. Aerial cable construction on the other hand has been in use long enough to indicate that construction will almost never go down during the severest storms. In the extreme cases in which a break does occur the circuits in the cable probably will continue to give service. An example of how modern toll cable construction enables service to be given even if the poles are broken

and the cable is thrown to the ground was shown in the case of a cable pole line between Maywood and Elmhurst, suburbs of Chicago. This line which was blown down in May 1927, during a wind storm of great severity carried two toll cables and also a subscribers cable. Although over a mile of pole line was blown down, the only trouble which occurred was due to a crack in the sheath at a splice which resulted in nine pairs being temporarily out of service out of a total of 845 pairs in the two toll cables.

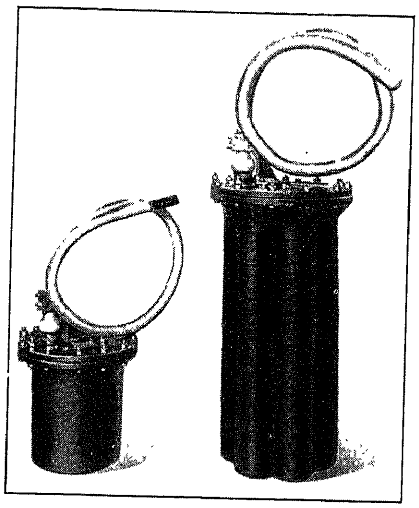

FIG. 6—COMPARATIVE SIZE OF LOADING COIL CASES

Each case containing 200 loading coils:
Left—Permalloy Core Coils—Weight 725 pounds
Right—Iron Core Coils —Weight 1750 pounds

Cable plant must of necessity be added in rather large units with fairly large margins over immediate requirements. If future requirements are overestimated, this will result in an appreciable amount of idle plant investment, or if underestimated, uneconomical reenforcement or replacement becomes necessary. The provision of cable thus requires careful forecasts for long periods as to the probable traffic volumes and circuit requirements.

Even with the developments in cable and loading coils, which are discussed previously, the distance to which cable could be extended for toll purposes was limited, and it was necessary to use No. 13, and in some cases No. 10, gage conductors to meet transmission requirements. With the development of vacuum tube repeaters[4] and their availability for use with toll cable, the distances to which such cable could be economically extended was increased very greatly. Furthermore, as a result of the use of repeaters, it has been possible to reduce the gage of cable circuits, so that modern toll cables now seldom contain conductors larger than No. 16 gage, and the greater proportion of conductors in such cables is generally No. 19 gage.

The first installation of vacuum tube type repeaters in the Chicago region was in 1914 in connection with the transcontinental line. This was a small installation, and growth in repeaters in this territory continued at a fairly slow rate up to about 1924. This slow growth was due to the fact that it had been necessary to install practically no long toll cables other than that extending between Chicago and Milwaukee. Beginning with the year 1924, toll cable was rapidly extended in various directions from Chicago for distances of over 100 mi. The Chicago-New York cable, for example, was completed in 1925, and the Chicago-St. Louis cable, which lies almost entirely within the State of Illinois, was completed in 1926.

At the present time, there are approximately 750 repeaters in use in the territory of the Illinois Bell Company, a very large proportion of which is in the Chicago region. Fig. 7 shows the location of repeaters in this Chicago region.

Another problem which has come up in recent years, although not expected to be a recurring problem, is concerned with the quality of transmission. When toll circuits consist of only non-loaded open wire, the effect of the line on intelligibility is negligible, as circuits of this type are very nearly distortionless. The introduction of loading into the telephone plant, however, has brought with it a certain amount of restriction of the range of frequencies transmitted, varying in degree with different types of circuits. It is well known that loading has the property of cutting off or suppressing frequencies above a certain number of cycles, depending on the character of the loading.[5] One of the fundamental questions of loading has been to determine

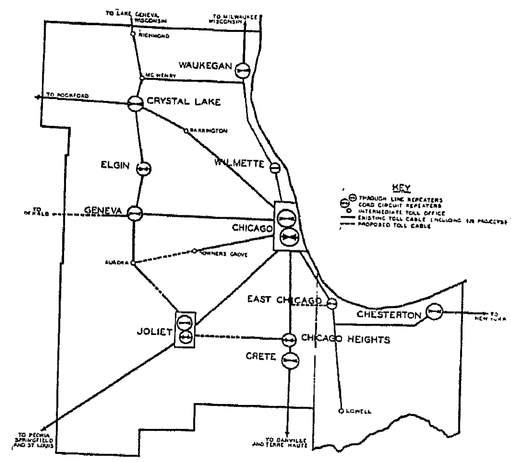

FIG. 7—LOCATION OF TELEPHONE REPEATER STATIONS AND THEIR RELATION TO THE TOLL CABLE NETWORK IN THE CHICAGO SUBURBAN AREA

4. See paper on *Telephone Repeaters*, by B. Gherardi and F. B. Jewett, TRANS. A. I. E. E., Vol. 38, 1919, p. 1287. Also by A. B. Clark on *Telephone Transmission on Long Cable Circuits*, TRANS. A. I. E. E., Vol. 42, 1923, p. 86.

5. See paper on *Development and Application of Loading for Telephone Circuits*, by Thomas Shaw and William Fondiller, TRANS. A. I. E. E., Vol. 45, 1926, p. 268.

what range of frequencies should be transmitted to furnish a satisfactory grade of speech without undue distortion. Early studies indicated that a cutoff frequency of about 2300 cycles would be satisfactory. These studies were based on measurements made by ear methods, however, and have been supplanted by more recent studies made by more scientific means. These studies show that it is economically practicable and desirable to set a limit of 2800 cycles as the minimum cut-off frequency in loaded cables, and accordingly all new toll plant is now designed on a basis of a cut-off frequency of 2800 cycles or better.

In Chicago, at the time the decision was made to adopt a higher cut-off frequency, there were installed about 50,000 loading coils in the local trunk plant. Many of these were on trunks which are used on toll connections, such as direct A-B and tandem trunks and toll switching trunks. These trunks had a cut-off frequency of 2300 cycles. A study of the Chicago city trunk plant showed that it was economically desirable to change the spacing of coils so as to raise the cut-off to 2800 cycles or better, and this work has now been practically completed so that all toll calls, with the exception of those involving a few circuits in some of the first toll cables installed, are now routed over trunks having the high cut-off features. As a net result of this increase in the cut-off frequency, a lower volume equivalent can be used, which means that a given type of loaded circuit can be used for a somewhat longer haul than if the cut-off were lower.

With the increasing complexity of the toll plant in recent years, it has appeared desirable to make periodical surveys of transmission conditions in a toll operating area to determine whether the existing plant is being used to best advantage from a transmission standpoint and to serve as a guide to the economical development of the toll plant during a period of say five years in the future. In considering the need for such a survey it should be noted that in the design of the toll plant, provision must be made for handling traffic which is switched to points beyond two given toll centers, as well as that which terminates at the two centers. This traffic for a given circuit group between two toll centers may amount to only a small percentage of the terminating traffic and means must be provided for taking care of transmission on such business which will not react seriously on the cost of providing facilities suitable for terminating business. Adequate transmission on switched calls may often be provided economically by the installation of repeaters[3] or by setting aside a certain proportion of circuits in a given circuit group for use in switched business and designing those circuits so they will be of a high enough grade to be used for either switched or terminating business. The economical location of repeater points and determination of the proper balance between circuits designed for terminating business and those designed for switched business can best be decided by a comprehensive study of transmission conditions for the entire area.

In making a transmission survey, an analysis of toll traffic is prepared covering the whole area for a representative month, showing both terminating and switched traffic and indicating the present transmission conditions as compared to the transmission objectives which have been established. By dividing the territory into natural subdivisions such that the traffic for different parts of the territory passes through a relatively small number of main switching points, it is often found that the analysis at a particular switching point will show that transmission improvement of a relatively small number of circuit groups will provide satisfactory transmission on all business switched through that particular point. It is also possible to pick out the particular centers where toll transmission under present conditions does not meet assumed objectives. A transmission study of this kind supplements the toll fundamental plan and is of assistance in the proper routing of toll traffic so as to fit in with expected future toll projects.

There are, of course, many other problems in the design of the toll plant relating not only to what might be termed transmission design but also methods of construction and problems of economics entering into the design of the plant. However, the greatest problem, as indicated in the earlier part of the paper, probably is that brought about by the extremely rapid growth taking place in the toll service requirements of the Chicago region.

Discussion

G. S. Dring: The importance of an equitable division of transmission losses in the trunk, substation, and toll-line facilities is stressed in this paper. Not only must the transmission of each unit be within the required limits, but the over-all transmission of the various units when connected together to form a toll circuit from subscriber to subscriber must be such as to provide a satisfactory talking channel from the subscriber's point of view.

This paper brings out the advantages from a service and maintenance standpoint of toll cable over open wire. It should be kept in mind, however, that while the use of toll cable does stabilize the service rendered over it, constant care must be exercised from the time it is installed and throughout its life to insure that the conductors are at all times in proper electrical and physical condition. Experience has taught that if we expect to make use of the phantom possibilities and avoid crosstalk from one pair to some other pair of phantom, we must make careful capacity-balance tests on the pairs of the various sections of cable before connecting them together, having in mind the desirability of keeping the unbalance between the various pairs and within quads to a minimum on the finished over-all cable. Further, the lead sheath must be kept air-tight or low insulation will result. Pressure tests by means of nitrogen or carbon-dioxide gas are made on sections of the cable before splicing is completed and thus any leaks or openings are located. After the cable is placed in service, insulation tests are made daily to insure that cracks or other openings have not occurred in the sheath.

Temperature also is a factor which must be compensated for, as an increase in temperature causes an increase in resistance of copper conductors thereby increasing the transmission loss for a given section. The longer aerial toll cables are divided into regulator sections of approximately 170 mi. each.

Transmission regulation made necessary on account of temperature changes is accomplished automatically by a wheatstone-bridge arrangement having for one arm a pair in the cable. A change in temperature affects this pair as it does the other pairs in service and the change in the regulator-pair resistance controls relays which increase or decrease the gain of the telephone repeaters associated with the working toll circuits at the regulator stations and thus compensate for increases and decreases respectively in temperature.

Signaling over long toll circuits is a subject in itself. Mr. Smith points out that the phantom coil does not permit d-c. signaling. The superimposing of d-c. telegraph circuits on toll circuits also makes d-c. signaling impracticable. The use of 135-cycle ringing current has been used on composited telephone circuits for a number of years and recently the use of 1000-cycle ringing current has been introduced over the longer-toll circuits. The 1000-cycle cycle ringing current has the advantage of being efficiently transmitted over telephone circuits as it is within the speech range.

H. S. Osborne: The extremely high losses in very long toll cable circuits have been referred to. These long toll cable circuits are made of copper totalling about 0.1 in weight the open-wire circuits which they displace, and the amount of loss per unit length is larger in an even greater proportion. Taking the cable circuits themselves, the loss of energy per unit length is 30 or 40 times as great as it is in large-gage, open-wire circuits. Whereas with ordinary terminal losses one could talk perhaps 400 mi. effectively on the open-wire circuits, the corresponding limit for these small cable wires would be 10 or 12 mi. Now, by the loading, which is discussed by Mr. Smith, that is raised to perhaps 50 mi., and then by the use of amplifiers the limit is very greatly extended.

The provision of proper energy efficiency is, however, only one of the electrical problems involved in establishing these circuits. Another one of great interest is the limitation of the distortion of speech. In order for the speech to remain clear it is necessary that the electrical efficiency of the circuit be very uniform over a relatively wide range of frequencies, about 200 to 2500 cycles. Bearing in mind that the loss of energy in a circuit from New York to Chicago is 10^{46}, it is evident that the regulation of that loss to a very uniform figure over a wide range of frequencies presents a very formidable problem. It has been necessary not only to make the cable circuits themselves as nearly distortionless as possible, but to compensate for the remaining distortion by compensating devices installed in connection with the repeaters.

These very long circuits have some extremely interesting transient current characteristics. The voice currents, as you know, consist of a series of discontinuous groups of high-frequency oscillations, and the impinging of these oscillations on the long cable circuits produces very important transient currents which it has been necessary to eliminate by attention to the method of design of the cable. These transient currents depend on the electrical constants of the cable itself.

Then there is another kind of transient current arising from the fact that the speed of propagation of the impulses is not infinite and, in fact, on the loaded cable circuits of a type used very widely, the velocity is about 12,000 mi. a second. At the distant end there is always a very considerable reflection of current because of an irregularity in the impedance of the circuit so that if such a circuit were to be used between New York and Chicago, the reflected current would come back after traveling 2000 mi. with a time lag of about $^1/_6$ sec., and on such a circuit one would hear the words coming back as a very distinct echo which is extremely annoying.

It has been necessary to do two things to reduce those echoes on the very long circuits. One is to design circuits with a higher velocity of propagation. The velocity on the circuits actually used between New York and Chicago is about 25,000 mi. a second. Another thing has been to make use of the voice currents themselves to suppress these so-called echo currents. That is done by having the voice currents operate a relay to short circuit the return path, and the time lag in the echo is sufficient to permit that operation to take place and cut off the echo currents before they have time to return.

Another very important series of problems, which constitutes a story in itself, is that of preventing interference between the circuits in the same sheath. In a toll cable there are on the average perhaps 250 independent circuits within a diameter of 2.5 in. To prevent those circuits from producing interference with each other, particularly where we are dealing with very great lengths and extreme ranges of energy input and output, has constituted an interesting and important series of problems.

As a final word, I should like to ask you to bear in mind that these circuits must be so designed and constructed that it is practical to maintain them without excessive expense. It is not possible to assign a high-grade man to watch over each particular circuit, but it must be possible to maintain the stability and the characteristics of the circuit by requiring only the attentions of men who have a great many duties to perform so that repeater stations, including several hundred repeaters, may be manned by only a relatively very small number of men.

A. P. Allen: It might be interesting to put a little background on this subject of the modern toll cable. When the line was first built between Chicago and New York in 1892, we couldn't put *any* cable in the line.

At that time we had no load coils, no repeaters, nothing but open wire. We had one thing, however, that made it possible to talk from Chicago to New York, and that was as nearly perfect maintenance as was ever found on a pole line.

Another thing that also came through the lack of toll cable, along in the late nineties, was due to the fact that we didn't know how to get enough open wires between New York and Philadelphia because they didn't have country roads enough for the requisite pole lines. So Mr. McCulloh, who is now president of the New York company, and I worked out a system of operating that gave us sixty paid minutes an hour over each circuit during the busy hour by an exact reversal of the present day A-B toll method. In other words, we had to pass our orders by telegraph wires, and we didn't allow even the toll operator to control, directly, a talking circuit between the two cities. They were all controlled by a switching operator at each end. The instant one circuit was taken down at one end it was put up on another connection. All the preliminaries were arranged on the order circuit before the customer was connected to the circuit, and lost circuit time was practically eliminated.

E. W. Vanderfield: Toll-operating methods are designed to furnish the briefest possible lapse of time between the placement and completion of a message compatible with proper economic costs and the necessities of the subscriber. As a consequence they involve a balance between operating costs and the expense of toll-circuit provision and between the manner of call placement and the resulting service speed.

For the shorter toll hauls of 50 mi. or less where the neighborhood conditions are conducive to relatively large traffic volumes, I believe it will normally be found that operating costs are the predominant factor and that these may be economically conserved through liberality in circuit provision.

Upon this basis if the subscriber is willing to transact his business with any one who may answer at the designated station rather than with a specified person and will furnish the station number, it is practicable and economical to provide a method of no-delay toll operation which is practically identical with local operation throughout its service features.

At ranges extending beyond 50 mi. this toll method has been considered inapplicable chiefly by reason of the supervision limits. At these longer hauls also the circuit costs become ascendant over the operating costs to a degree which makes it expedient to engineer and provide circuits upon a definite delay basis and to thus restrict the two-number operating field.

The increasing informality of toll message placements as signalized by the rise of station-to-station volumes with their significant speed and no-hang-up features, and the generally increasing volumes of toll traffic have together contributed to bring about a marked change in present toll methods. As a consequence it is now planned to extend this station-to-station service where the necessities of the subscriber permit by extending the duties of the recording toll operator to allow her to atte an immediate completion of all toll calls.

When the subscriber will place his call on a station-to-sta basis by giving the station number and where there is an toll-line circuit available in less than two minutes, the subscr will, I understand, secure his connection, regardless of dista upon the same basis as is now encountered for the short-l station-to-station service. This will represent the full possi ties of toll service as it is now seen.

If the station number is not known, a particular perso desired, or an idle toll-line circuit is not at once available, call must necessarily revert to a delay basis similar to that controlling under present toll-board practise where direc service must be rendered and ticket-distributing time is invol

It can be reasonably expected that this method will en between two and three minute service to be given upon a ma ity of the toll-board-offered calls with no reaction upon present average speed for the remaining traffic and wit directly resulting in increased circuit or operator provision.

The Vacuum Tube Rectifier

Oscillographic and Vacuum Tube Voltmeter Study of its Application to B-Voltage Supply for Radio Receivers

BY JOHN H. KUHLMANN[1]
Member, A. I. E. E.
and
JAMES P. BARTON[2]
Enrolled Student

***Synopsis.**—This paper covers investigations made in undertaking the design of a rectifier for use as the B power supply for radio receivers. It determines the most satisfactory type of filter circuit and the appropriate values of inductance and capacitance to give a d-c. output delivered with the least practicable voltage drop and having no fluctuations of sufficient magnitude to interfere with the proper operation of the set. A vacuum-tube peak voltmeter used to detect very small fluctuations is described.*

THE object of this investigation was to determine a good method of design for a vacuum-tube rectifier for converting alternating current into direct current equivalent to that obtained from a battery. The d-c. output should be such that it can be used to properly operate a radio receiving set and loudspeaker without introducing any interference or modulation from the a-c. source. The study of the the eliminator was prompted by the lack of engineering literature[3] on the subject and by the desire of the writers to more fully understand the proper design, the characteristics, and the limitation of the device.

The study is divided into several sections:

1. The rectifier vacuum tubes.
2. Oscillographic study of the action of inductance and capacity (alone and in combinations), upon the rectified wave form.
3. Vacuum tube peak voltmeter study of the small ripple in the load current and its elimination by use of two section filters.
4. Calculation of per cent voltage fluctuation.
5. Conclusions.

The eliminator to be investigated consists of three distinct units,

1. The rectifier proper
2. The filter
3. The load resistance for dividing the load voltage.

The units which make up the general circuits under study are shown in Fig. 1. In Fig. 2 is shown the completed eliminator and its parts as used in this study.

SECTION 1. THE RECTIFIER VACUUM TUBES

The vacuum tubes used for the rectifier were the obsolete power tubes, UV-202, being the only tubes available at the time. Three tubes were tested; their plate current-voltage and plate current-resistance curves are given in Figs. 3 and 4, respectively.

From the plate voltage-current curves in Fig. 3 it is seen that the tubes T_1 and T_3 saturate at a much lower current density than T_2, which was an unused tube. T_1 and T_3 had both been used as oscillators; T_3 used longer than T_1. These curves show that if the rectifier is required to give a peak current of over 100 milli-

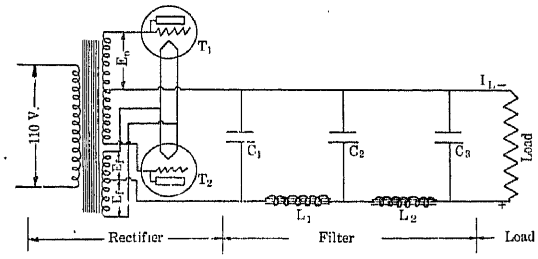

FIG. 1—CIRCUIT DIAGRAM OF EXPERIMENTAL VACUUM TUBE RECTIFIER

Rectifier:
E_p = 300 volts effective from center-tapped transformers
E_f = 3.75 volts effective from center-tapped transformer
T_1 = T_2 = U V 202 5-watt power tubes with grid connected to plate
Filter:
C_1, C_2, C_3 are 500-volt condensers. Several values of capacity were used in the experiment
L_1 and L_2 are similar iron-cored inductances each having an inductance of about 30 henrys for the normal d-c. excitation. The cores are in two laminated sections, each *L*-shaped; butt joints are used giving small variable air-gaps. Each coil contains about 6200 turns with an average resistance of 645 ohms
Load:
Low-inductance, wire-wound variable resistance units of ample current capacity. Resistors for final set are wound on flat strips of bakelite and are of fixed value. Several values of resistance were used in the experiments

amperes, the rectified current wave will be flat topped.

The plate current-resistance curves, (Fig. 4), were obtained to show the variation of plate resistance with the rectified current. These curves are desirable in order to match tubes and thus obtain equal amplitudes in both halves of the rectified wave.

In the oscillograms, Fig. 2B, V_1 and V_2 show the current wave forms as per T_1 and T_2, and V_3 gives the resulting current I_L, in the resistance load of 8000 ohms. The values of V_1, V_2, and V_3 were taken simultaneously. The circuit diagram is shown in Fig. 2A.

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1. Assistant Professor of Electrical Design, University of Minnesota.
2. Minneapolis, Minnesota.
3. See "Theoretical and Practical Aspects of Low Voltage Rectifier Design When Employing the Three-Electrode Vacuum Tube" by R. D. Duncan, Jr., *Radio Review*, Vol. III, 1922, pp. 59-71 and pp. 114-124. "The Production of Constant High Potential With Moderate Power Capacity" by A. W. Hull, *G. E. Review*, Vol. 19, 1916, pp. 173. "The Thermionic Vacuum Tube" by Van Der Bijl, Chapter VI, McGraw Hill, New York. "Alternating Current Rectification" by L. B. W. Jolley, Chapter X, John Wiley & Sons, New York.

Presented at Regional Meeting of District No. 5 of the A. I. E. E., Chicago, Ill., Nov. 28-30, 1927.

The wave forms V_4 and V_5, Fig. 2B, show the resulting current in the load and the 60-cycle e. m. f. applied to the rectifier, respectively. The oscillograms show that the rectified current is in phase with the applied voltage. This is to be expected, as there is practically no reactance in the load circuit.

The half wave rectifier gives a load current wave form as shown in Fig. 2B by V_1 or V_2.

The current wave forms, instead of the voltage,

Fig. 2—Assembled Rectifier with Filter

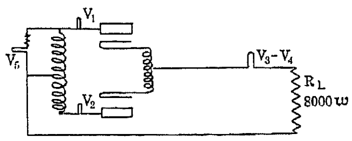

Fig. 2A—Circuit Diagram of Rectifier Without Filter

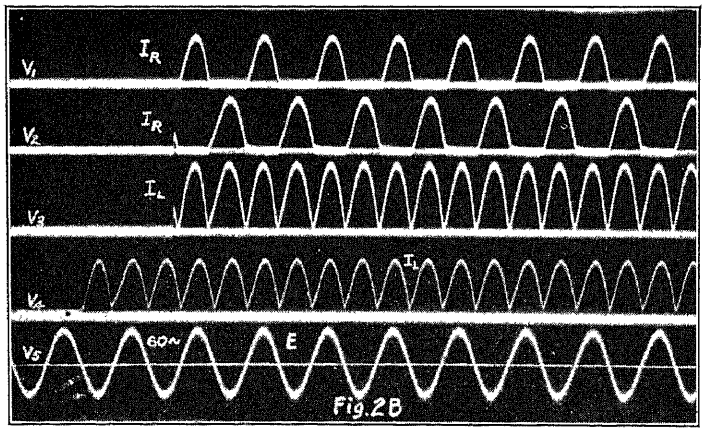

Fig. 2B—Oscillograms for Rectifier Circuit Fig. 2A

V_1 and V_2 are individual tube output currents. V_3 and V_4 are load current for full-wave rectifier. V_5 is 60-cycle applied voltage

were observed throughout this study because the current consumed by the voltage element of the oscillograph is a large portion of the total rectified current and therefore would disturb the circuit and current conditions to be studied.

Section 2. Oscillographic Study of the Action of Inductance and Capacity Alone and in Combination Upon the Rectified Wave Form

The Effect of Capacity on the Load Current Wave Form. The addition of capacity across the load resistance of a rectifier, as in Fig. 3A, reduces the ripple in the load current. The operation of the condenser may be explained as follows: When the voltage is applied to the rectifier, the condenser takes a charge and continues

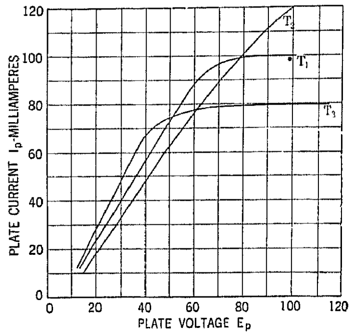

Fig. 3—Plate Current—Voltage Characteristic of Three *U V*-202 Vacuum Tubes

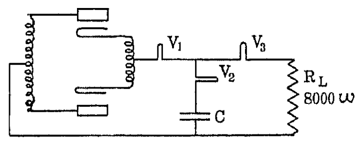

Fig. 3A—Circuit Diagram of Rectifier with Capacity Shunted Across Load Resistance

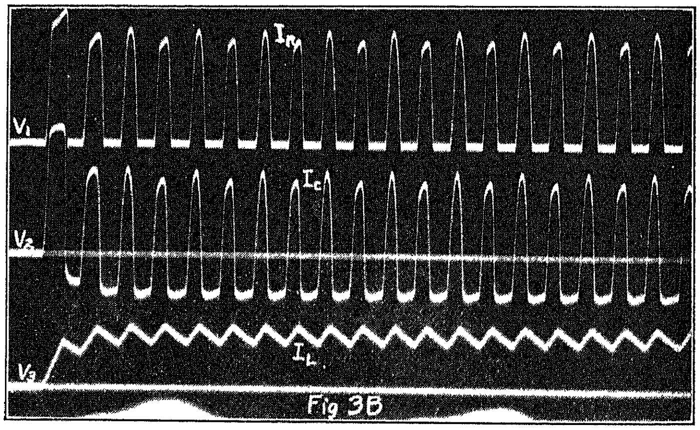

Fig. 3B—Oscillograms for Rectifier Circuit Fig. 3A

V_1 is rectifier current. V_2 is condenser current. V_3 is load current with 2.13 μ f. shunt capacity

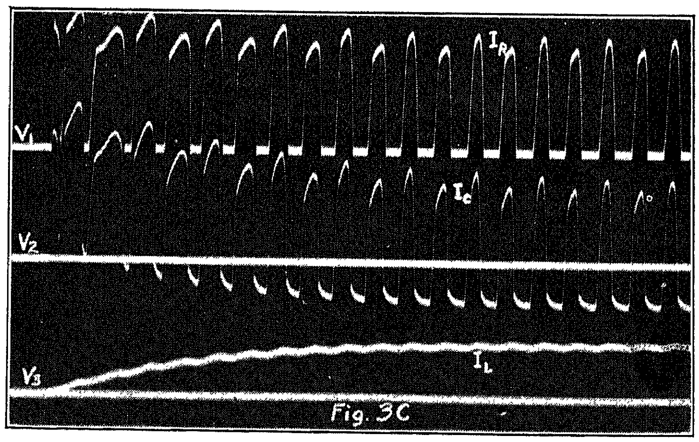

Fig. 3C—Oscillograms for Rectifier Circuit Fig. 3A

V_1 is rectifier current. V_2 is condenser current. V_3 is load current with 12.13 μ f. shunt capacity

charging until the rectifier voltage reaches its maximum value. As soon as the rectifier voltage begins to decrease, the condenser begins to discharge and in so doing, builds up a voltage across the tubes which opposes the applied voltage. The rectifier current wave, therefore, takes the shape shown by V_1, Fig. 3B, instead of that shown by V_3, Fig. 2B. The condenser continues to discharge until the decreasing condenser

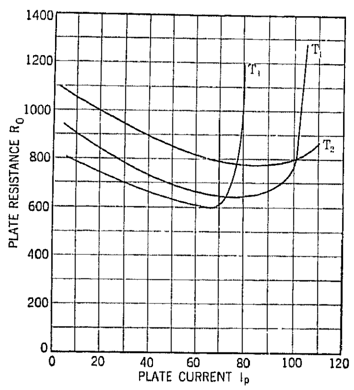

FIG. 4—PLATE CURRENT—RESISTANCE CHARACTERISTIC OF *U V*-202 VACUUM TUBES

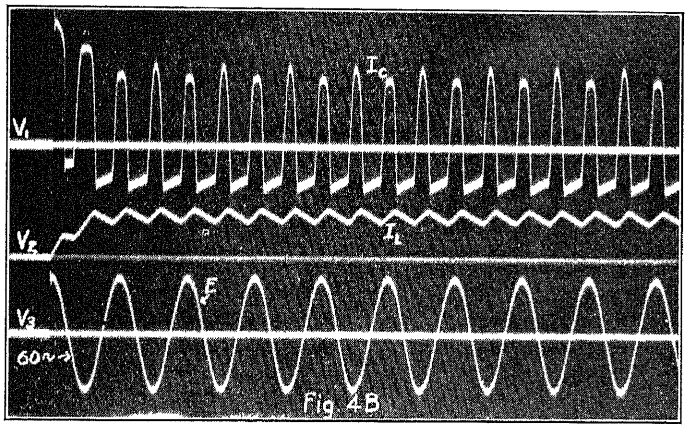

FIG. 4B—OSCILLOGRAMS FOR RECTIFIER CIRCUIT FIG. 3A

V_1 is condenser current. V_2 is load current with 2.13 μ f. shunt capacity. V_3 is 60-cycle applied voltage

voltage becomes equal to the increasing rectifier voltage. The load current pulsations are of much smaller amplitude for the circuit shown in Fig. 3A than for the circuit shown in Fig. 2A, because the condenser discharges through the load resistance and supplies the load current during the time the rectifier voltage is passing through zero. The condenser discharges through the load resistance in accordance with the law for the discharge of a condenser through a resistance; that is,

$$i = \frac{E}{R} \epsilon^{-\frac{T}{RC}}$$

From the above discussion, it appears that it should be possible to reduce the load current ripple by increasing the time of discharge of the condenser. For a circuit such as shown in Fig. 3A, the time constant,

$$T = R\,C$$

Since the load resistance is fixed, the time constant can only be increased by increasing the capacity. Fig. 3B shows the load current when the shunt capacity is 2.13 microfarads and Fig. 3C shows the load current for a shunt capacity of 12.13 microfarads. The oscillograms show that the ripples in the load current are very much less for a shunt capacity of 12.13 microfarads than for a capacity of 2.13 microfarads.

In Fig. 4B, the relation between the condenser current V_1, the load current V_2, and the impressed 60-cycle

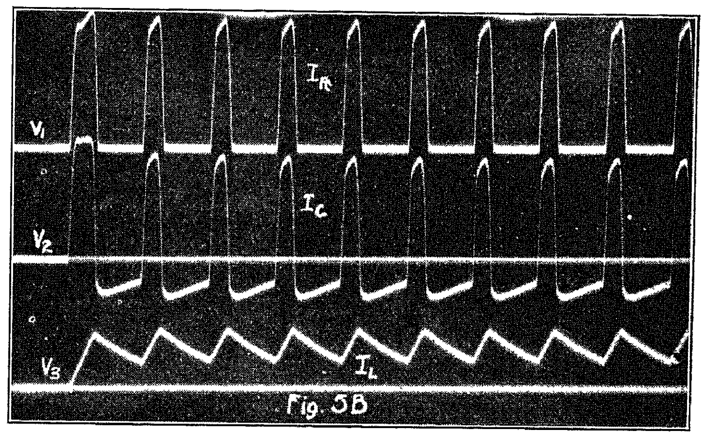

FIG. 5B—OSCILLOGRAMS FOR RECTIFIER CIRCUIT OF FIG. 3A

V_1 is rectifier current. V_2 is condenser current. V_3 is load current with 2.13 μ f. shunt capacity

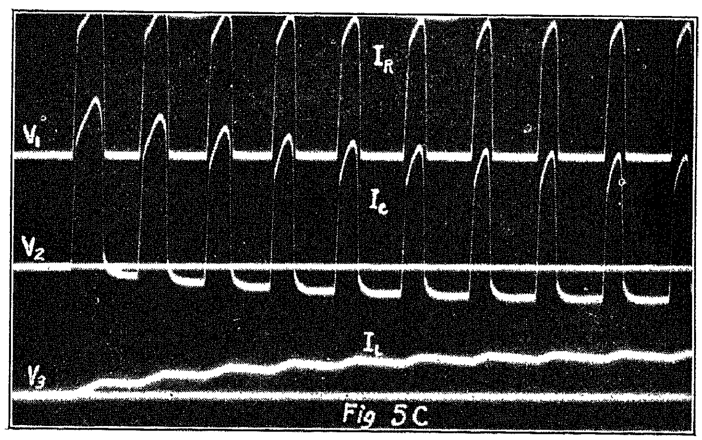

FIG. 5C—OSCILLOGRAMS FOR RECTIFIER CIRCUIT FIG. 3A WITH ONE TUBE

V_1 is rectifier current. V_2 is condenser current. V_3 is load current with 12.13 μ f. shunt capacity

e. m. f. V_3, is shown. The value of C_1 is 2.13 microfarads. The upper waves of V_1 show very well the dissimilar characteristics of the rectifier tubes. It is well to point out that in V_1 the wave forms above the axis represent the charging current, and below the axis, the discharge current into the load.

Removing either T_1 or T_2 from the circuit Fig. 3A

gives a half wave rectifier. The oscillograms in Figs. 5B and 5C show the effect of shunt capacity across the load resistance on the output current of the half wave rectifier. In Fig. 5B, C_1 is 2.13 microfarads; in Fig. 5C, C_1 is 12.13 microfarads. In both of these oscillograms, V_1, V_2, and V_3 are taken simultaneously, with V_1 the rectifier output current, V_2 the condenser current, and V_3 the resulting load current. In V_2 the wave forms above the axis give the charging current, and below the axis, the discharge current to the load.

Effect of Inductance on the Load Current Wave Form.

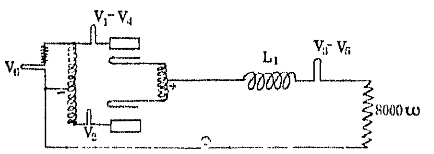

FIG. 6A—CIRCUIT DIAGRAM OF RECTIFIER WITH INDUCTANCE IN SERIES WITH LOAD RESISTANCE

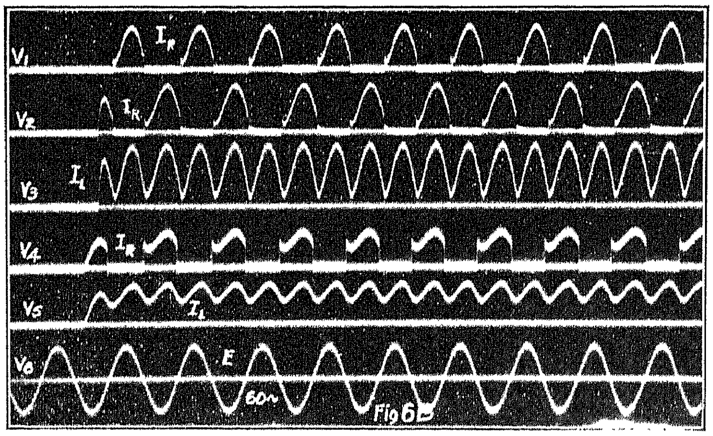

FIG. 6B—OSCILLOGRAMS FOR RECTIFIER CIRCUIT FIG. 6A

V_1 and V_2 are individual tube output current. V_3 is load current with L_1 7.5 henrys. V_4 is output current of one tube. V_5 is load current with L_1 = 30 henrys. V_6 is 60-cycle applied voltage

Introducing inductance into the load circuit, as illustrated in Fig. 6A, causes a reduction in the amplitude of the current ripple and also a large drop in the effective load voltage, because of the high $I Z$ drop of the inductance. On the other hand, the shunt capacity as shown in Fig. 8A gives a higher effective load voltage than is obtained when both L and C are out of the circuit. This effect of the condenser is obvious from the discussion given above.

In the oscillogram of Fig. 6B, V_1, V_2, and V_3 were taken simultaneously with L_1, having an inductance of approximately 7.5 henrys, while V_1 and V_2 show the individual tube output and V_3 the load current. The small hooks on the wave forms of V_1 and V_2 show that the rectified current lags the impressed e. m. f. because of the series inductance.

The effect of increasing the series inductance to approximately 30 henrys is shown (Fig. 6A) by V_4, V_5, and V_6 in Fig. 6B, V_4 being the output of one tube (the output of the other tube being the same), V_5 the load current, and V_6 the impressed e. m. f. The ripple of V_5 is considerably smaller than that of V_3, and the hooks on the wave forms of V_4 are larger, indicating a greater angle of lag between current and impressed e. m. f. Furthermore, the load current ripple is now practically a sine wave of a frequency twice the input frequency of 60 cycles.

Increasing the inductance still further has only a very small effect on the load current ripple. Half wave rectification, with inductances in the load only, gives a slightly disturbed upper half of a sine wave. The oscillograms for the half wave rectifier are not shown here.

It has been demonstrated above that the amplitude of the load current ripple is reduced by increasing the

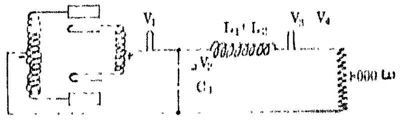

FIG. 8A—CIRCUIT DIAGRAM OF RECTIFIER WITH SERIES INDUCTANCE AND CAPACITY SHUNTED ACROSS RECTIFIER

C_1 = 12.13 μ f. $L_1 + L_2$ = 60 henrys

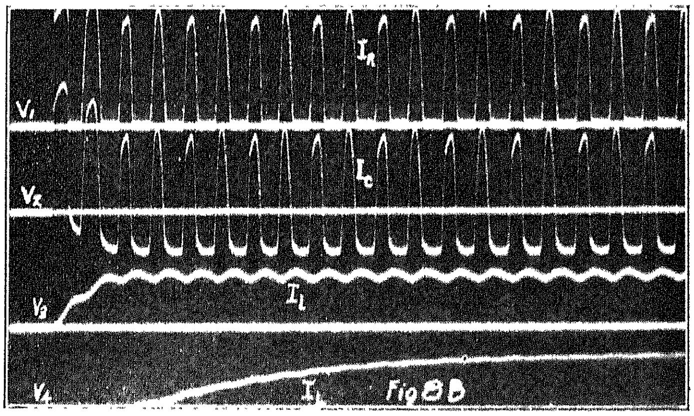

FIG. 8B—OSCILLOGRAMS FOR RECTIFIER CIRCUIT FIG. 8A

V_1 is rectifier current. V_2 is condenser current. V_3 is load current with 2.13 μ f. shunt capacity. V_4 is load current with 12.13 μ f. shunt capacity

time constant of the load circuit. For the circuit shown in Fig. 6A, with an inductance of L_1 = 50 henrys and a series resistance of 9000 ohms, the time constant is 0.00555 sec. The circuit in Fig. 3A with C_1 = 12.13 microfarads and a load resistance of 8000 ohms has a time constant of 0.097 sec. Therefore, the amplitude of the load current ripple should be much less for the circuit with shunt capacity than for the circuit with series inductance. This is clearly shown by the oscillograms, V_3 Fig. 3C, for the circuit with shunt capacity and V_5 Fig. 6B, for the circuit with series inductance.

Effect of Inductance and Capacity on the Load Current Wave Form. The effect of capacity shunted across the

load resistance and the effect of inductance in series with the load resistance on the amplitude of the load current ripple have been shown above. By properly proportioning inductance and capacity, therefore, it should be possible to reduce the amplitude of the load current ripple to a negligible value.

In oscillogram Fig. 8B, for the circuit of Fig. 8A, V_1, V_2, and V_3 were taken simultaneously, V_1 showing the current from the rectifier, V_2 the condenser current with 2.13 microfarad capacity, and V_3 the load current.

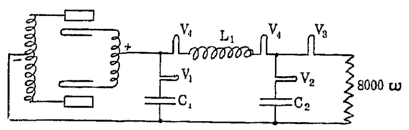

Fig. 9A—Circuit Diagram of Rectifier

Series inductance L_1 is 30 henrys. C_1 is 4.26 μ f. C_2 is 4.76 μ f.

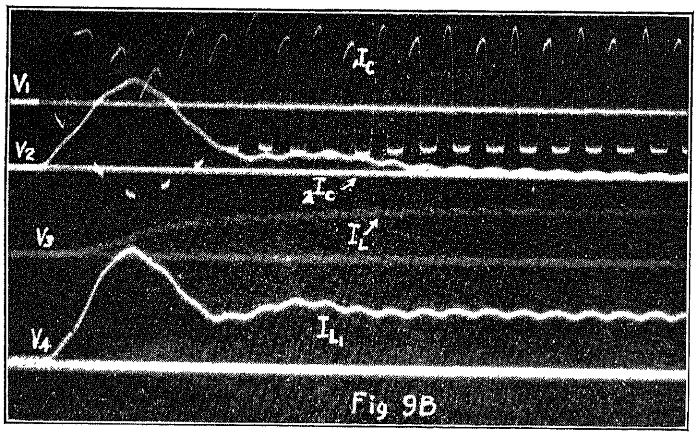

Fig. 9B—Oscillograms for Rectifier Circuit Fig. 9A

V_1 is condenser current C_1. V_2 is condenser current C_2. V_3 is load current. V_4 is current in series inductance

Increasing C_1 to 12.13 microfarads gives the load current shown by V_4, which is practically a straight line. The per cent ripple in this load current is 1.2 per cent and was determined by the method explained in Section 3 of this paper. With the oscillograph, the current shown by V_4 appears as a straight line. It is seen, therefore, that the oscillograph will not show a ripple which is less than about 2 per cent. Since a load current with a ripple of 2 per cent is not satisfactory for "B" battery supply for radio receiving sets, further filtering and other means for detecting the ripple are necessary.

Two more interesting oscillograms are shown to give the action of the second condenser in the filter shown in Fig. 9A. In the oscillogram of Fig. 9B for the circuit shown in Fig. 9A, V_1, V_2, and V_3 were taken simultaneously, with V_1 the condenser current of C_1, V_2 the condenser current of C_2, and V_3 the load current; V_4 is the inductance current and was taken separately, although timed nearly the same.

A starting transient is observed here, and is due to the charging of C_2, which had no charge at the start. The transient is observed to be slightly oscillatory but so damped that only two cycles are apparent. The effect is more pronounced in V_4. In the steady state, C_2 draws a small current, being charged by the 120-cycle current ripple and discharging into the load, thus reducing the load ripple still further. The load current, V_3 Fig. 9B, shows a smooth line.

The circuit, Fig. 10A gives an inverted L filter. Oscillograms, Fig. 10B, show V_1 the inductance current, V_2 the condenser current, and V_3 the load current, taken simultaneously, with C_2 equal to 2.13 microfarads. The wave forms V_4, V_5, and V_6 show these same currents but with C_2 increased to 12.13 microfarads.

Several interesting things are to be observed: First, the highly damped oscillatory transient due to the charging of C_2; second, on account of large shunt capacity and a proper series inductance, the ripples in the load current are less pronounced. Increasing the capacity, C_2, increases the transient and gives a smooth load current.

Section 3. Measurement of the Load Current Ripple by the Vacuum Tube Peak Voltmeter

The output current of a vacuum tube rectifier was found to be a pulsating current as illustrated in Fig. 2B.

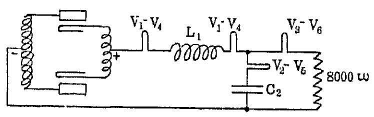

Fig. 10A—Circuit Diagram of Rectifier with Inverted L Filter

L_1 = 30 henrys, C_2 = 2.13 or 12.13 μ f.

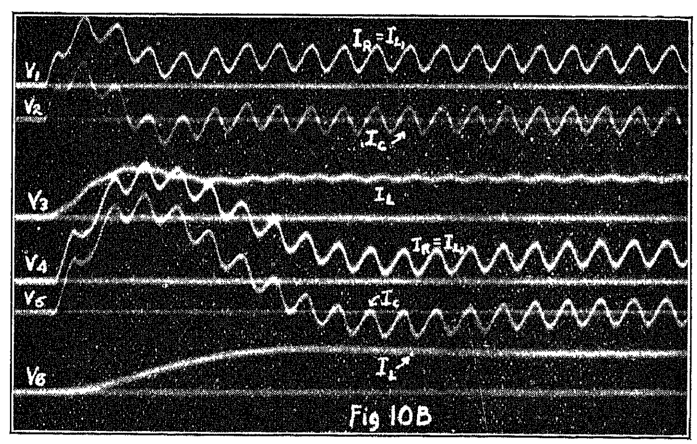

Fig. 10B—Oscillograms for Rectifier Circuit Fig. 10A

V_1 is inductance current. V_2 is condenser current and V_3 is load current when C_1 = 2.13 μ f. V_4 is inductance current, V_5 is condenser current and V_6 is load current when C_1 = 12.13 μ f.

It has been shown that the amplitude of the pulsations can be reduced by means of a filter with properly proprotioned series inductances and shunt capacities. It was also shown that the oscillograph would not detect a ripple in the load current less than 2 per cent. But a ripple of 2 per cent in the load current of a vacuum tube rectifier is too large for "B" battery supply for radio

receiving sets; therefore, the following method for measuring the current ripple was developed.

A current ripple may be looked upon as a periodic alternating current of some wave form superimposed upon a constant direct current. In this case of the output of a vacuum tube rectifier through a filter, the superimposed alternating current is practically a sine wave of 120-cycle frequency. By measuring the two

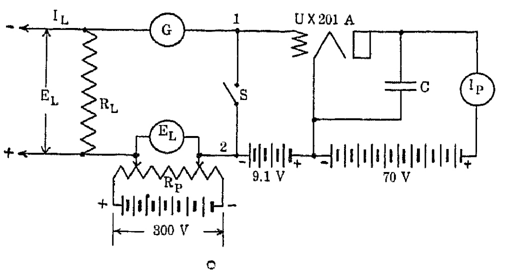

FIG. 11—CIRCUIT DIAGRAM OF VACUUM TUBE VOLTMETER

G = galvanometer. E_L = d-c. voltmeter. I_p = milliameter
R_L = rectifier load resistance

components of the load current, the ripple may be expressed in per cent by

$$\frac{I_{mac}}{I_{dc}} \times 100$$

Here I_{mac} is the maximum value of the a-c. component and I_{dc} is the d-c. component of the rectifier current. After analyzing several methods for measuring these two components of the load current, it was found that the vacuum tube voltmeter would probably be the most satisfactory. The results obtained show that this method is well suited for such measurements.

Fig. 11 shows the circuit diagram of the voltmeter as used for these tests. Here R_L is the load resistance of the rectifier, E_L the load voltage, and I_L the load current, which contains the ripple. A d-c. potentiometer circuit, capable of a voltage variation from 0 to 300 volts, is in series with the grid-filament circuit. The purpose of this potentiometer is: (1) to balance out the effect of the d-c. component and keep it from biasing the grid, (2) to measure the value of the d-c. component of the load voltage indicated by the meter E_L. When the switch S is closed, the galvanometer G is used to determine if the potentiometer voltage is equal to the d-c. component of the load voltage. The meter I_p indicates the plate current.

Since the plate current of a vacuum tube is a function of the applied grid voltage, this device can be calibrated and used as a peak voltmeter. The meter was calibrated by passing a known 60-cycle current through a known non-inductive resistance and applying the $I R$ drop to the terminals 1-2 of the meter with the switch S open. Normal grid bias, plate voltage and filament current were used. Since the voltmeter was calibrated on 60 cycles and used on 120 cycles, there is a possibility of a slight error in the readings, due to the fact that the plate current meter I_p will not read the 60-cycle and 120-cycle pulses the same. The error is so slight, however, that it can be neglected.

The calibration curve for this meter is shown in Fig. 12. Two calibration curves are shown, one from zero to 11 volts, and the other from 10.5 to 57 volts. In order that no grid current shall flow, the peak voltage to be measured should not exceed the value of the grid biasing battery voltage, in this case, 9.1 volts. With the grid at a positive potential of 15 volts, the grid current is negligible in comparison with the load current, 0.05 amperes, and therefore voltages up to 25 volts can be measured with a high degree of accuracy and higher voltages can be measured with nearly the same degree of accuracy. The plate current shown by the calibration curves in Fig. 12 is not biased to zero. This is done so that a known zero can be maintained and any deviation noted and corrected. The low-range calibration curve is a close approximation to the plate current-grid voltage static characteristic curve of the UX-201A vacuum tube.

To use the vacuum tube voltmeter, the grid, filament, and plate battery voltages are adjusted to their proper calibrated values. With the complex current in the load resistance, the approximate value of E_L is determined and the potentiometer set to that value. The switch S is closed and R_p varied until the meter G reads zero. Then S is opened and the reading of I_p noted. The corresponding value of the a-c. component of the load voltage is obtained from the calibration

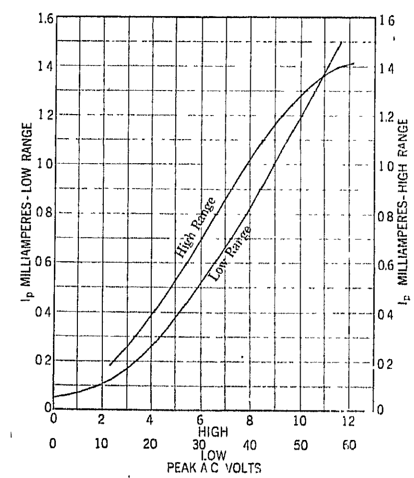

FIG. 12—CALIBRATION CURVE FOR VACUUM TUBE VOLTMETER

curve, Fig. 12. The reading of E_L gives the d-c. component. From these two values, the per cent ripple can be calculated as explained above. In order to obtain satisfactory results, the voltage applied to the rectifier must be constant because very slight changes in the primary voltage will produce large variations in the voltmeter readings across the load. For these tests a constant a-c. voltage was obtained from a synchronous motor-generator set with battery excitation on the generator.

The various filter circuits shown in Fig. 13 were studied with the vacuum tube voltmeter, for which purpose, the full wave rectifier was used with a load resistance of 5100 ohms. With this resistance across the rectifier and no filter, an r. m. s. load current of 0.050 amperes was obtained. The load voltage E_L obtained with the different filter circuits with constant input voltage is shown in the figure. The effect of varying the shunt capacity for each of the filter circuits

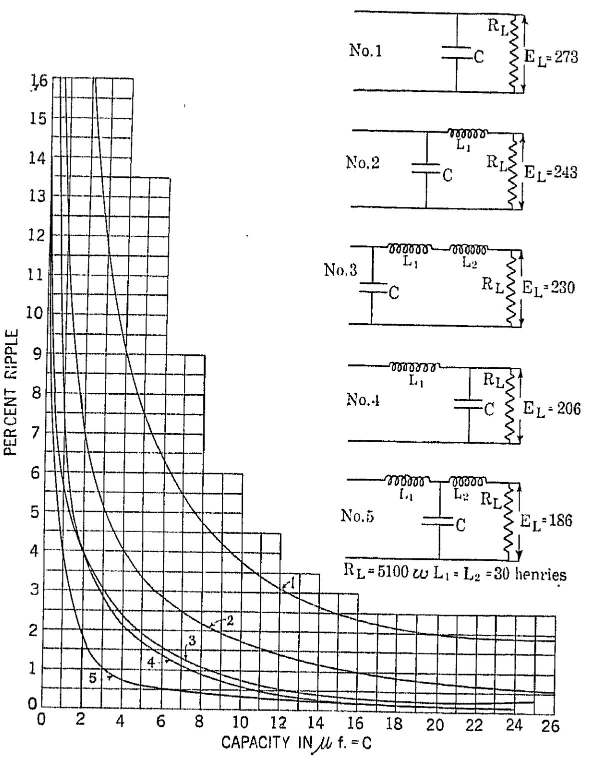

FIG. 13—EFFECT OF VARYING CAPACITY IN VARIOUS TYPES OF FILTER CIRCUITS

is also shown in Fig. 13. The results of these tests show that the filters with a small per cent ripple in the load voltage have a high-voltage drop. By combining several of the types of filters shown, one with a small per cent ripple and a low-voltage drop can be obtained.

One section of a Pi-type filter with the test results is shown in Fig. 14, and a single section of a T-type filter with test results is shown in Fig. 15. The Pi-type filler gives a current with a smaller ripple and also has a lower voltage drop than the T-type filter. The T filter can be improved by adding a capacity C_2 across the load as shown in Fig. 16. The results of the test show that the per cent ripple has been reduced to a negligible value, but that the voltage drop in the filter remains unchanged. By adding a third capacity C_1, as shown in Fig. 17, the desired results are obtained; that is, the ripple is reduced to a value that cannot be detected by the voltmeter and the voltage drop is the same as for the Pi-filter shown in Fig. 14.

By inserting a pair of high-resistance receivers in the plate circuit of the vacuum tube voltmeter, the ripple can be detected audibly. A ripple that was just audible was found to be equal to 0.08 per cent. To check these results, a small portion of the load voltage was impressed upon the terminals of a 1 to 6 audio-frequency transformer and the secondary connected to the terminals 1-2 of the vacuum tube voltmeter. With a plate current of one milliampere, the hum was just audible. This method of test was used for the circuit shown in Fig. 17. When using the audible method of detecting the ripple, it was found that the removal of the shunt capacity across the load (C_3, Fig. 17) introduced a bad circuit noise caused by high frequencies in the load current. It was also noted that a capacity of at least two microfarads should be used, at C_3 Fig. 17, to by-pass the high frequencies that tend to enter the load.

The circuit devised for measuring the two components

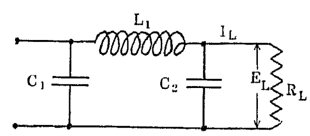

FIG. 14—E_L = 250 VOLTS, I_L = 0.049 MILLIAMPERE

C_1 μ f.	C_2 μ f.	Per cent ripple
2.13	5	0.30
4.26	5	0.20
4.26	10	0.08

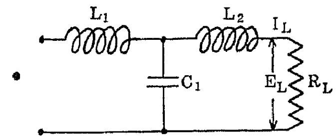

FIG. 15—E_L = 186 VOLTS I_L = 0.037 MILLIAMPERE

C_1	Per cent ripple
2.13	1.62
4.26	0.70
9.26	0.40
14.26	0.27

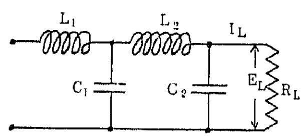

FIG. 16—E_L = 186 VOLTS I_L = 0.037 MILLIAMPERE

C_1	C_2	Per cent ripple
5.0	2.38	0+
5.0	4.76	0+
10.0	4.76	0+

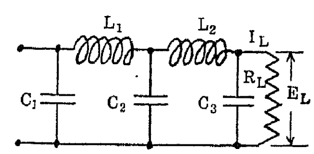

FIG. 17—E_L = 250 VOLTS I_L = 0.049 MILLIAMPERE

C_1	C_2	C_3	Remarks
2.13	5	2	Slight hum
4.26	5	2	Very slight hum
4.26	5	4	Not audible
4.26	10	4	Not audible

FIGS. 14, 15, 16, AND 17—FILTER CIRCUITS WHICH WERE TESTED

The amount of ripple and the load voltage for different condenser values are shown herewith. In all cases L_1 and L_2 equal 30 henrys each and R_L equals 5100 ohms

of the load current by means of the vacuum tube voltmeter is believed to be a new application for this type of instrument.

SECTION 4. CALCULATIONS OF PER CENT VOLTAGE FLUCTUATION

The percentage voltage fluctuation in the load resistance may be calculated by the formulas given by H. T. Van Der Bijl in his book above mentioned. For the type of filter shown in Fig. 8A, the formula is as follows:

$$\frac{\delta E_L}{E_L} = \frac{2\pi}{\omega C_1 \sqrt{R_L^2 + L^2 \omega^2}}$$

$C_1 = 12.13 \times 10^{-6}$ farads, $L = L_1 + L_2 = 60$ henrys, $R_L = 8000$ ohms, and $\omega = 2\pi \times 120 = 754$. The calculations give a percentage voltage fluctuation of 1.49 per cent. The value obtained from the measurments by means of the vacuum tube voltmeter is 1.2 per cent.

For the type of filter shown in Fig. 9A, the following formula applies:

$$\frac{\delta E_L}{E_L} \quad \frac{2\pi}{\omega C_1 [R_L^2 (1 - L_1 C_2 \omega^2)^2 + L_1^2 \omega^2]^{1/2}}$$

$C_1 = 4.26 \times 10^{-6}$ farads, $L_1 = 30$ henrys, $C_2 = 5.0$ 10^{-6} farads, $R_L = 8000$ ohms, and $\omega = 2\pi \times 120 = 754$. The calculations show a percentage voltage fluctuation of 0.289 per cent. The vacuum tube voltmeter method of measuring the percentage fluctuation gave 0.20 per cent.

Section 5. Conclusions

In order that the voltage drop in the filter circuit should not be too high, the series inductance should not be larger than required to produce a current without ripples. For the filter circuits discussed above, each inductance for the working load current should not be less than 25 henrys. The resistance of each inductance should preferably be kept low,—not greater than 250 ohms. To further reduce the voltage drop, a shunt capacity of not less than four microfarads should precede the inductances to provide a low impedance shunt for the ripple current.

To obtain a rectified current with negligible ripple, two Pi-type filter sections will generally be the maximum number required if shunt capacities equal to, or larger than, four microfarads are used. A single Pi-type filter section can be used to give a ripple of approximately 0.10 per cent if both condensers have a capacity of six microfarads, or larger, and if the series inductance is large, 25 henrys or larger.

Discussion

H. S. Read: Filters have too long been submerged in elegant mathematics. Now we all see what is contributed by the parts of the filter and how filters may be compared. The authors do much to bring theories out of the secrecy of certain laboratores and put them in practical forms.

It is remarkable that a filter can be used for radio. One must greatly reduce the a-c. component in the direct current to make the a-c. inaudible. The reduction is a noteworthy feat because the human ear responds to a tremendous range of exceedingly small engeries. By way of illustration, if one-half inch represents the least sound energy which can be heard, how long a ruler would measure the loudest sound which one can hear without pain? Two-thirds the distance to the sun! Or, if all the talk since colonial days of all the people in the United States were paid for at a common rate for electrical power, you could pay for all the talk with $5.39. We use in everyday life a great range of intensities and very small sound energies. It is amazing that filters can really prevent the hum in radio. The authors show how it is done.

C. M. Jansky, Jr.: There are several characteristics of rectifier devices and filters used in receiving sets which are rather interesting, and which apparently are causing some discussion among the manufacturers of such equipment. One of the characteristics of rectifiers is that they usually have fairly high internal resistance with the result that for varying loads the voltage delivered varies widely. That is to say the voltage regulation of the device is extremely poor.

There has been some attempt on the part of manufacturers to adopt standard specifications for rectifiers, and in so doing consideration has been given to the establishment of a standard filter circuit and also a standard load. The specifications for rectifying devices would then be given in terms of the action in this particular circuit.

The conclusion was drawn that if rectifier A, in the standard circuit gave such and such results, and rectifier B gave such and such results in the same standard circuit, for circuits having entirely different characteristics you could predict what the results would be, which I think, to anyone who has considered the points brought out in the paper by Professor Kuhlmann and Mr. Barton, looks offhand as though too much were taken for granted. Therefore, any light which can be cast on the action of these devices should be very helpful.

J. P. Barton: This particular B-battery eliminator which we have studied is of a general type of those which are on the market at the present time.

Because of the apparent lack of proper engineering design and knowledge in regard to the inductances, and, furthermore, of the relatively high internal plate impedance of the rectifier tubes, the voltage regulation is usually poor. For this particular circuit described, the resistance of the inductances is higher than we have recommended in our conclusions, and this coupled with the high internal plate impedance of the rectifier tubes gave, for this set described in the paper, a voltage regulation of about 23 per cent over the useful range.

There is one other point I should like to bring up which has very seriously, in the past years, concerned the B-battery eliminators, and that is the proper design of the series iron-core inductances so that they will maintain a high enough value of inductance to cause a proper degree of filtering when normal load current is flowing through them.

Many inductances on the market have no air gap in the magnetic circuit. Such inductances will usually become saturated when 60 to 100 miliamperes, which is about the normal d-c. flowing in the average B-battery eliminator, is passed through them. Such inductances under these conditions have a very low value of effective a-c. inductance because the working or incremental permeability is low at high inductions corresponding to partial saturation. The ripple consequently would be very high in the load. It is only in a few of the manufacturing companies that the proper design of such inductances is understood. Several men have presented papers in the past several years on the design of such reactors. These papers have made it possible for many to design a reactor at the present time that will carry a d-c. component and yet maintain a high degree of a-c. inductance and keep that inductance over a small variation of the d-c. component which is present in these filter circuits.

E. W. Vanderfield: I should like to ask Mr. Barton what is is the effect of the transformer regulation on the transformer supplying the plate voltage to the rectifier. That varies a good deal with the load drawn from the transformer, I believe.

J. P. Barton: In the work done here we maintained an input voltage of 300 volts a-c. to the tubes and measured the variation of load voltage due to the effect of different filters. This variation in input voltage was small because the output current variation was over a small range. If such a rectifier were built for varying loads, then it would be quite essential that the plate transformers should have good voltage regulation. However, where a system is built to supply a constant load, then the voltage regulation is not so important unless the primary voltage varies unduly.

The main difficulty in reducing the high voltage regulation of the B-battery eliminator is in the high internal plate impedance of the rectifiers, and the high resistance of the chokes, this latter usually due to economic reasons.

A Two-Range Vacuum Tube Voltmeter

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Associate, A. I. E. E.

and

C. B. FELDMAN†
Enrolled Student, A. I. E. E.

Synopsis.—The design, uses, and limitations of a new circuit employing the three-element vacuum tube as a voltmeter are discussed. Two overlapping ranges of voltage, together with a single operating battery, are the unique features. The effect of wave-form and the elimination of that effect are treated.

THE need for a convenient means of measuring small alternating voltages has long been felt in the communication engineering field. The usual type of electromagnetic voltmeter is inadequate for two reasons: (1) Comparatively large current is required to operate it, and (2) its calibration is greatly affected by frequency. Both of these defects are more or less inherent and can probably never be materially reduced. The electrostatic voltmeter, while possessing neither of these defects, has others. Its sensitivity is exceedingly low, requiring the use of an optical system for voltages less than about 25 volts, and its adjustment is very difficult.

The versatile vacuum tube, however, possesses certain characteristics which make it applicable to the measurement of alternating voltages.

Various types of vacuum tube voltmeters are possible. One type uses a variable grid bias voltage which is made to balance out the plate current resulting when an alternating voltage is applied to the grid. This type measures peak voltages. Other types rely upon detector action of the tube. The voltmeter circuit described in this paper uses the grid bias method of detection; this is sometimes also called plate circuit detection.

Fig. 1 shows in schematic form the circuit which will be discussed. In order to obtain a wider range of voltage and still prevent grid current from flowing, two sets of plate and grid bias voltages are provided for. To obtain a means of rigidly fixing both of these voltages, they are taken as resistance drops in the filament circuit. The use of a UX-199 tube, requiring but 60 milliamperes for the filament, makes it possible to supply all power to the circuit from 45-volt, "B" batteries. Best results are obtained when two large-sized, 45-volt units are used in parallel. One set of resistances is used for the low-voltage range, the other for the higher range. When the higher range is in use, the grid is biased beyond the point where plate current normally disappears. For a fixed battery voltage, there exists an optimum proportion of voltages to give both the best, greatest sensitivity and the maximum range.

Since the resistance in the plate circuit is low (of the order of several hundred ohms), the plate current may be considered as vanishing at a bias voltage equal to the plate voltage divided by μ.

Let

E = available battery voltage,

E_b = supplied plate voltage (high range) which equals the voltage between plate and filament for high range,

e_b = supplied plate voltage (low range) which equals the voltage between plate and filament for low range,

E_c = absolute value of grid bias voltage used with high range,

e_c = absolute value of grid bias voltage for low range, optimum value,

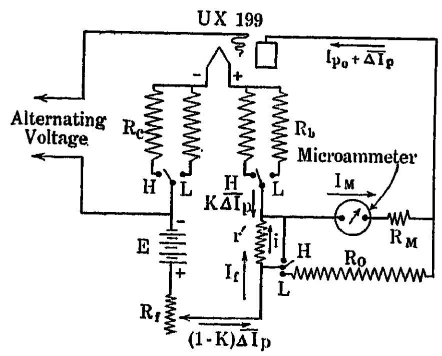

FIG. 1—SCHEMATIC DIAGRAM OF VACUUM TUBE VOLTMETER

V = maximum peak voltage which can be measured on high range without grid current flowing, ($V = E_c$)

v = maximum peak voltage which can be measured on low range without grid current flowing,

a = voltage which when added to e_c would reduce the plate current to zero; see Fig. 2.

Then,

$$e_c = \frac{e_b}{\mu} - a \text{ (a is positive)} \tag{1}$$

For the high range,

$$E_c - \frac{E_b}{\mu} \leq v \tag{2}$$

in order to provide continuity between the two ranges. Also, for the high range,

$$E_b = E - E_c \tag{3}$$

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Putting $E_c = V$ into (3) and combining with (2),

$$V - \frac{E - V}{\mu} \leqq v \qquad (4)$$

For the low range,

$$e_b = E - b - e_c \qquad (5)$$

where b is the auxiliary balancing voltage used in the low range to balance out the normal plate current, I_{p_0}, and which was available in the high range for plate and bias voltage. Putting $e_c = v$ into (5) and combining with (1),

$$v = \frac{E - b - v}{\mu} - a \qquad (6)$$

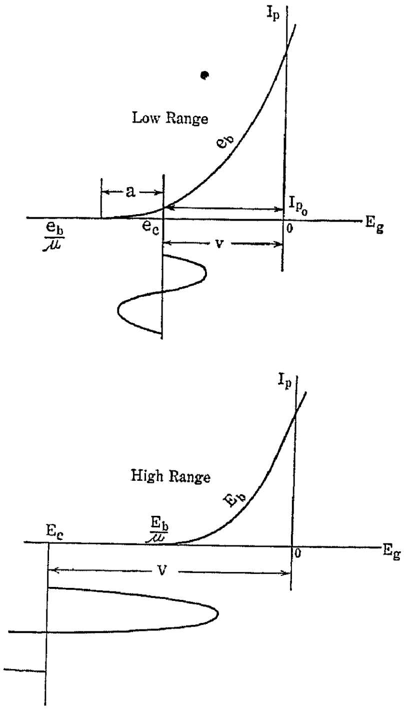

Fig. 2—The Double-Range Design

e_b = plate battery voltage
= plate filament voltage
e_c = operating bias
μ = voltage amplification factor of tube

Eliminating v between (6) and (4) gives

$$V \leqq (E - b - \mu a)\frac{\mu}{(\mu + 1)^2} + \frac{E - V}{\mu + 1} \qquad (7)$$

This equation expresses the maximum peak voltage measurable in a continuous two-range design, in terms of available battery voltage, voltage amplification factor and two design constants, a and b.

The constant a is determined by trial and was found to be of the order of one volt for several 199 tubes. Its value is not critical. The constant b is quite arbitrary, if R_e is adjustable for different tubes having different values of I_{p_0}, being equal to $I_{p_0} R_e$. For R_e = 50,000 ohms, b proved to be about three volts for one tube and five volts for another, using a 45-volt "B" battery as the source of voltage.

Using the guiding equations derived above, the voltages, E_c, E_b, e_c, e_b, were selected and the resistances shown in Fig. 1 were obtained on the basis of 60-microampere filament current. Thus, E_c is determined by Equation (7), E_b by (3), e_c and e_b by (4) and (5), respectively. These values are not critical. A filament rheostat of 30 ohms was used so the maximum drop would be greater than 1.5 volts, permitting the

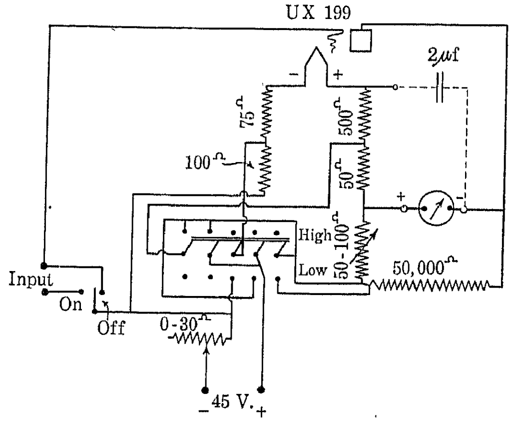

Fig. 3—Wiring Diagram of Assembled Voltmeter

e_c = 4.5 volts
e_b = 33 volts
E_c = 10.5 volts
E_b = 30 volts

use of dry cells to compensate for drop in B-battery voltage. The resistance r' was variable but could be rigidly set for a particular tube. It was found necessary to use a variable 100-ohm rheostat to accommodate the three tubes tested. There is a considerable difference between the normal plate currents for different tubes.

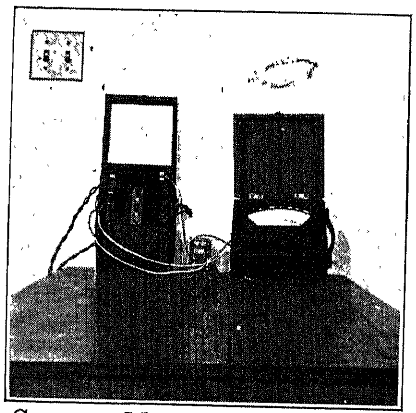

Fig. 4—Cabinet, Microammeter, and Condenser

In fact, in the tube used in obtaining the data for this paper, a current of nearly two microamperes flows at the high bias, whereas in the other tubes tested, the plate current had entirely vanished at that bias.

The final arrangement is shown schematically in Fig. 3. A telephone key is used to change from one range to the other. A key is also provided to disconnect the voltmeter from the alternating voltage. This key

short-circuits the voltage terminals when the voltage is disconnected, in order to prevent the rise in plate current accompanying the free grid. The entire assembly of tube resistances and keys is mounted in a wooden case as shown in Fig. 4. Terminals are provided for the battery and the microammeter. In the tests herein described, a Rawson-type 501 microammeter having three ranges, 0-20, 0-200, 0-2000 microamperes, was used. An expensive calibrated instrument is not necessary, however; any D'Arsonval galvanometer movement provided with a scale and giving a readable deflection on a few microamperes will prove satisfactory. A more sensitive meter is not desirable due to difficulty which will be experienced in maintaining the false zero. In fact, slight fluctuations in battery voltage as well as shocks applied to the tube are observable on the 0-20-microampere range. The resistances are of the porcelain, tube-wound type and are not especially non-inductive. In the experimental work a condenser was sometimes used across the plate-filament as is shown in dotted lines in Fig. 3. The tube is mounted in a shock-absorbing socket.

Referring to Fig. 1, the application of Kirchoff's Laws to the balancing circuit gives the following equation:

Let

$$I_{po} = I_p \text{ when } I_M = O$$
$$I_f r' = I_{po} R_o \qquad (8)$$

When an alternating voltage is applied to the grid, a mean increase in plate current, $\overline{\Delta I_p}$, occurs. In flowing from the filament, this increase divides between the two filament terminals in the ratio K as shown in the figure.

Thus, when $I_p = I_{po} + \overline{\Delta I_p}$,

$$(I_{po} + [1 - K]\,\overline{\Delta I_p} - i)\,R_o - (I_f + i)\,r' - (K\,\overline{\Delta I_p} + i)\,R_M = 0 \qquad (9)$$

But

$$K\,\overline{\Delta I_p} + i = I_m \qquad (10)$$

Combining (8), (9), and (10),

$$I_M = \overline{\Delta I_p}\,\frac{R_o + K\,r'}{R_o + R_M + r'} \qquad (11)$$

Equation (11) shows that the calibration is not independent of meter resistance. The lowest range of the Rawson microammeter has a resistance of about 1000 ohms which is not negligible compared with R_o = 50,000 ohms. The variation between the resistance of meters of various manufacture but of similar range, however, is not sufficient to cause more than 1 per cent error. Equation (11) gives the relative meter current in terms of the actual $\overline{\Delta I_p}$, K, and the resistances R_o, r', and R_M. It is to be recognized that changes in R_M as well as changes in filament rheostat (as made to compensate for falling battery voltage) theoretically change the actual mean increase by virtue of changing the plate circuit resistance. The value of K is also affected. No attempt has been made to obtain a mathematical statement of this; the effect is imperceptible. A further effect of varying the filament rheostat is to cause a slight change in the voltage applied to the circuit through the $\overline{\Delta I_p}$. R_f drop. This drop for the 30-ohm rheostat is negligible, also, being less than about 0.01 volt.

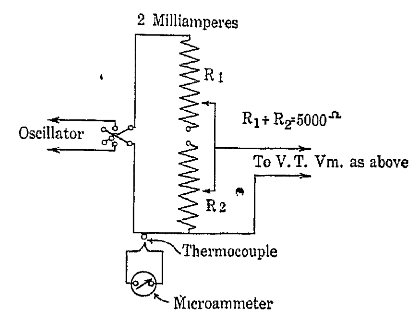

FIG. 5—CALIBRATION CIRCUIT

The following factors determine the usefulness of a tube voltmeter in communication measurements:

1. Variation of calibration with frequency,
2. Input impedance,
3. Variation of calibration with wave-form,
4. Sensitivity,
5. Range,
6. Stability of calibration.

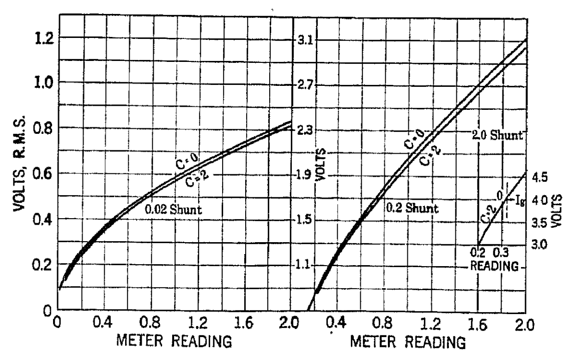

FIG. 6—SAMPLE CALIBRATION VACUUM TUBE VOLTMETER

Low range 1000 cycles
Low range zero = 0 on 0.02 shunt

Information concerning all of these factors has been obtained in the laboratory.

Fig. 5 shows the circuit used to calibrate the tube voltmeter. This circuit was also used for much of the test work. Calibration curves for the model studied in the laboratory are shown in Figs. 6 and 7. In addition to the fact that grid current reduces the input impedance, it biases the grid differently when flowing

through different resistances. Tests made using no grid bias verified this. The flow of grid current thus limits the range.

In order to interpret some of the subsequent results more intelligently, the effect of wave-form will be treated now. A consideration of the manner in which the mean increase in plate current arises shows that, in general, wave-shape does affect calibration. For almost all of the test work, the source of alternating current was a Western Electric 8-A oscillator comprising an oscillator, voltage amplifier, and power amplifier. Under load, the wave-form of the output current departs considerably from a sine-wave.

For the purpose of studying the effect of wave-form, oscillograms were taken of the current wave at different loadings. A precision-type radio-frequency milliammeter was used to maintain the current at a constant r. m. s. value of 20 microamperes for each load. The voltage drop to actuate the voltmeter was taken across a General Radio decade resistance box so that the voltage wave had substantially the same form as the current wave.

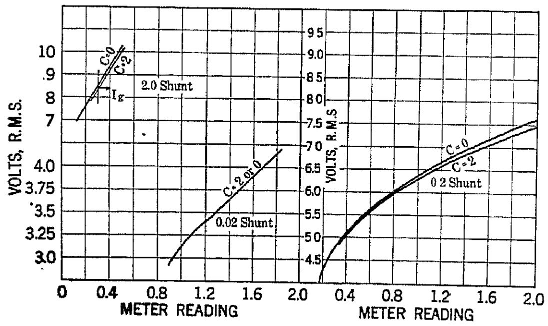

FIG. 7—SAMPLE CALIBRATION VACUUM TUBE VOLTMETER

High range 1000 cycles
High range zero = 0.14 on 0.02 shunt

Oscillogram (*a*) of Fig. 8 shows the wave-form with the oscillator loaded most heavily; (*b*) shows the wave-form under light load; and (*c*) shows the form improved slightly by means of a parallel "trap" circuit, tuned to 400 cycles, the frequency used. The following table gives the results:

TABLE I
FREQUENCY = 400 CYCLES PER SEC.

Volts r. m. s.	Reading	Zero scale	Reading	Scale	Cond. m. f.	Wave-form	Volts from curve	Per cent error
7.00	0.18	0.02	1.755	0.2	0	*a*	7.36	+4.90
*7.00	0.18	0.02	1.252	0.2	0	*a*	6.73	* −4.01
7.00	0.18	0.02	1.433	0.2	0	*b*	6.97	−0.42
*7.00	0.18	0.02	1.388	0.2	0	*b*	6.90	* −1.45
7.00	0.18	0.02	1.460	0.2	0	*c*	7.00	0
*7.00	0.18	0.02	1.403	0.2	0	*c*	6.93	* −1.01
7.00	0.18	0.02	1.890	0.2	2	*a*	7.40	+5.40
7.00	0.18	0.02	..	0.2	2	*b*	..	..
7.00	0.18	0.02	1.518	0.2	2	*c*	6.96	−0.57
0.70	0	0.02	1.345	0.02	0	*a*	0.701	+0.14
0.70	0	0.02	1.340	0.02	0	*b*	0.700	0
0.70	0	0.02	1.340	0.02	0	*c*	0.700	0

*Oscillator terminals reversed.

The per cent error in the above readings was referred to the reading with wave-form (*c*), designated by zero error for the reason that it coincided with the calibration. It can be seen that while none of the wave-forms photographed is so distorted as to be considered unsuitable for most work, errors in measurement may result if tube voltmeters are used, unless precautions are taken to eliminate them.

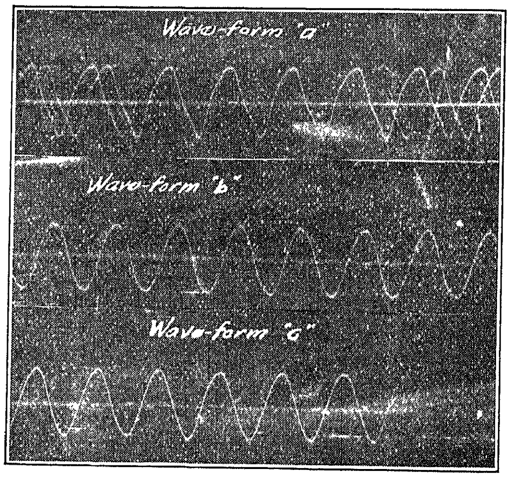

FIG. 8

The curves given in Fig. 9 show that the calibration does not vary appreciably with frequency. For each set of curves, a constant voltage across a non-inductive resistance was obtained by the aid of a precision thermal milliammeter. As would be expected, the use of a condenser connected between plate and filament prevents the slight falling off of the curves for higher frequencies due to the inductance in the plate circuit.

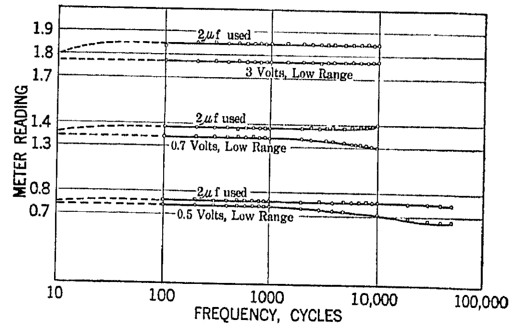

FIG. 9—FREQUENCY CHARACTERISTIC OF VACUUM TUBE VOLTMETER

A two-microfarad condenser gave just as satisfactory results as one of larger value.

The input impedance of the tube voltmeter was measured with a shielded capacity bridge. The voltmeter was set up as for usual operation and the input impedance was obtained as a function of indicated plate current; see Fig. 10. The input capacity was found to be approximately 30 $\mu\mu$f. and the input conductance was found to be of the order of 0.004 micromhos. The conductance increases rapidly as the grid approaches a positive potential. At 1000 cycles, the impedance is about five megohms.

The above measurements show that the input im-

pedance of the vacuum tube voltmeter is entirely satisfactory for use in most communication engineering measurements. The device cannot be used to measure voltage across a condenser unless a conductive path exists between condenser plates, inasmuch as the voltmeter has no grid leak of its own.

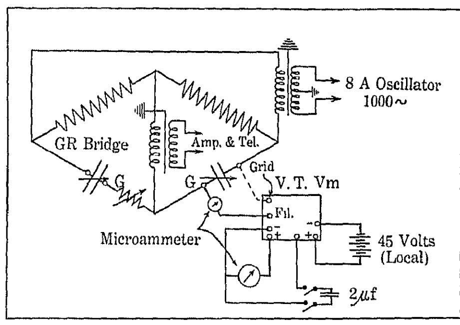

Fig. 10—Schematic Diagram of Impedance Bridge

Further notes on the method of calibration may be of interest. A frequency of 1000 cycles per sec. was used in the circuit shown in Fig. 5. The current was kept constant at two milliamperes and the load was kept fixed at 5000 ohms, non-inductive. The thermocouple, which was of the heater coil type, was calibrated with two milliamperes direct current immediately before use. The wave-form from the oscillator was satisfactory as the oscillator was not overloaded. Reversal of oscillator terminals had but little effect. Calibration curves were obtained both with and without two microfarads between the plate and filament. Condenser curves should be used for all frequencies about 100 cycles; below 100, the no-condenser curves should be used.

A re-calibration of the voltmeter described, made after about 40 hours of service, was found to coincide with the original calibration to within the limits of accuracy of the standardizing voltage. This is to be expected, as the method of adjusting for the false zero compensates for any change in emission. The change in filament current necessary to so compensate makes insignificant change in the operating voltages. As the tube nears the end of its life, however, its characteristics will change and compensation for the change in emission will not suffice, in general, to retain the calibration.

Aside from the use of the vacuum-tube voltmeter as a calibrated instrument to measure voltages, there is a wide field of use in which the device may be used as an intermediary, in measuring a ratio of voltages. An illustration is the comparison of two impedances. In Fig. 11 is shown the scheme for comparing a scalar impedance with a resistance. The voltmeter is first connected across Z_x and the deflection noted, or the oscillator output is adjusted to give a conveniently readable deflection; it is then transferred to the voltage divider which is adjusted to give the same deflection. Care must be taken, if the wave-form is unsymmetrical with respect to the axis, to impress the same side of the wave toward the grid. In comparing an impedance of high phase-angle with a resistance, error arises even then if the wave-form is bad; for the harmonics in the current wave contribute to the voltage in different degrees in the reactance and resistance. This is exemplified by the fact that the measured impedance is different for reversed oscillator terminals, using the correct voltmeter connections as shown in Fig. 11. Measurements comparing the impedance of a 100-millihenry inductance with that of a resistance showed a discrepancy of the order of 5 per cent upon reversing oscillator terminals. When an inductance was connected in series with the resistance and the impedance of the resistance reduced to the same value as that of the inductance, thus making the phase angles in the two impedances equal, this discrepancy disappeared. Excellent sensitivity was obtained. The error of measurement was less than 0.5 per cent.

The tube voltmeter circuit under discussion cannot be used, without modification, except where the arithmetic mean of the voltage measured is zero. Measurements are frequently desired, however, of inductance or alternating voltage in iron core coils, transformers, etc., while carrying a polarizing or magnetizing current. One method of making such measurements is to employ the grid stopping condenser type of voltmeter. As pointed out by W. B. Medlam and U. A. Oschwald,* this type of voltmeter, however, has inherent objections such as enormous wave-form error, restricted range, and some frequency error. A preferable means of making the above measurements for transformers is to employ the plate detection voltmeter in a circuit shown in Fig. 12

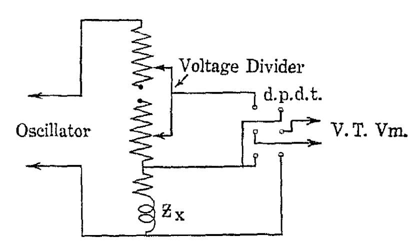

Fig. 11—Comparison of Impedances Using Vacuum Tube Voltmeter

which was suggested to the authors by Mr. J. P. Barton, late of this laboratory, now of the Westinghouse Electric & Mfg. Co. By making r sufficiently low, of the order of a few hundred ohms, the current taken by the transformer can be reduced to a negligible amount; or, if not, corrections can be readily applied. Very satisfactory results have been obtained with this circuit in measuring voltage ratios of transformers, the manipulation being similar to the comparison of impedances. Here, the wave-form error cannot well be eliminated by a choice of voltmeter connections, and the best solution is to employ a good wave-form which, of course, is desirable from all standpoints.

Elimination of Wave-Form Error

Writing I_p as a function of E_g alone, as can be done

*Bibliography, 1.

when the plate circuit impedance is very low and E_p remains substantially constant,

$$I_p = f\,(E_g)$$

Let the steady current and voltage be I_{po} and E_{go}, respectively, and express the superposition of a variation in E_g as

$$I_{po} + \Delta\, I_p = f\,(E_{go} + \Delta\, E_g)$$

Expanding this by Taylor's theorem,

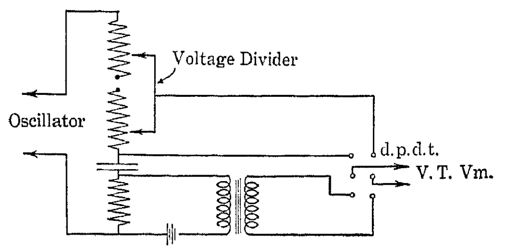

Fig. 12—Circuit for Measuring Transformer Characteristics

$$\Delta\, I_p = \Delta\, E_g \cdot \frac{d\; I_p}{d\; E_g} + \frac{\Delta\, E_g^2}{2} \cdot \frac{d^2\, I_p}{d\, E_g^2} + \frac{\Delta\, E_g^3}{6} \cdot \frac{d^3\, I_p}{d\, E_g^3} + \ldots$$

In general, this series would not greatly facilitate the study of the effect of wave-form where the variations E_g and I_p are wide, inasmuch as then the derivatives would vary over the range. In particular, however, if $I_p = A\,(K + E_g)^2$, the second derivative is constant $(= 2\,A)$ and all higher order derivatives vanish. Under this condition,

$$\Delta\, I_p = \Delta\, E_g \cdot \frac{d\; I_p}{d\; E_g} + \frac{\Delta\, E_g^2}{2}\, \frac{d^2\, I_p}{d\, E_g^2} \cdot\cdot\cdot \quad (1)$$

It now becomes possible to compare $\Delta\, I_p$ for two unlike wave-forms A and B,

Let

$$\Delta\, E_{g_A} = {}^{M}E_A \sin\, \omega\, t \quad \ldots \quad (2)$$

and let

$$\Delta\, E_{g_B} = {}^{M}E_{B_1} \sin\, \omega\, t + {}^{M}E_{B_2} \sin\,(2\,\omega\, t + \alpha_2) + {}^{M}E_{B_3} \sin\,(3\,\omega\, t + \alpha_3) + \ldots + {}^{M}E_{B_n} \sin\,(n\,\omega\, t + \alpha_n) \quad (3)$$

Further, let

$${}^{M}E_A = \sqrt{{}^{M}E_{B_1} + {}^{M}E_{B_2} + \ldots + {}^{M}E_{B_n}} \quad (4)$$

to express equal r. m. s. values. Substituting (2) in (1) and integrating over a fundamental cycle to obtain the average change in plate current, $\Delta\, I_p$,

$$\overline{\Delta\, I_{p_A}} = \frac{1}{2} \cdot \frac{d^2\, I_p}{d\, E_g^2} \cdot \frac{1}{2\pi} \int_0^{2\pi} [{}^{M}E_A \sin\, \omega\, t]^2\, d\,(\omega\, t)$$

as the periodicity of the first term causes it to vanish. Performing the integration,

$$\overline{\Delta\, I_{p_A}} = \frac{d^2\, I_p}{d\, E_g^2} \left[\frac{{}^{M}E_A^2}{4} \right] \quad (5)$$

Now, substituting (3) in (1), gives for the mean change,

$$\overline{\Delta\, I_{p_B}} = \frac{d^2\, I_p}{d\; E_g} \cdot \frac{1}{4\,\pi} \int_0^{2\pi} \Bigg[\sum_{K=1}^{n} {}^{M}E_{B_K}^2 \sin^2\,(K\,\omega\, t + \alpha_K) + \sum_{\substack{r=1 \\ r \neq s}}^{n} \sum_{s=1}^{n} {}^{M}E_{B_r}\, {}^{M}E_{B_s} \sin\,(r\,\omega\, t + \alpha_r) \sin\,(s\,\omega\, t + \alpha_s) \Bigg]\, d\,(\omega\, t)$$

The integrated value of the first summation can be shown to be

$$\pi \left[{}^{M}E_{B_1}^2 + {}^{M}E_{B_2}^2 + \ldots + {}^{M}E_{B_n}^2 \right]$$

while the integrated value of the double summation is zero over the cycle. The mean change in plate current then becomes

$$\overline{\Delta\, I_{p_B}} = \frac{d^2\, I_p}{d\, E_g^2} \left[{}^{M}E_{B_1}^2 + {}^{M}E_{B_2}^2 + \ldots + {}^{M}E_{B_n}^2 \right]$$

By (4) we have

$$\overline{\Delta\, I_{p_B}} = \overline{\Delta\, I_{p_A}}$$

which shows that for the quadratic characteristic the wave-form error vanishes. In special cases, the discrepancy between two unlike wave-forms may vanish for a non-quadratic function, but this will not be so in general, as a consideration of the graphical treatment clearly shows.

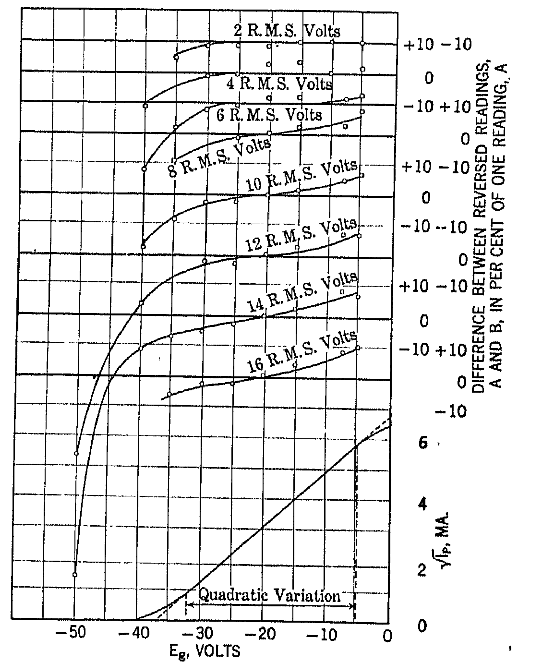

Fig. 13—Variation of Wave-Form Error with Bias

The significant thing about the above demonstration is that the vacuum tube voltmeter may be freed from its greatest limitation by confining the range of variation of grid voltage to a substantially quadratic portion of the curve. No previous treatment of this fact by others has been found by the authors.

Certain types of tubes display characteristics well suited for use in eliminating wave-form error. The low-μ power tubes, in general, have a relatively wide range of grid voltage over which the characteristic is

quadratic. Fig. 13 shows the plot of the square root of plate current as a function of E_g for a UX-171 tube, and shows a range of about 27 volts over which the straight line indicates a constant second derivative. That the wave-form error is negligible over this region is shown by the other experimental curves of Fig. 13. They show the percentage difference between reversed readings for the unsymmetrical wave-form (*a*), previously referred to. The percentage is taken with respect to the readings reversed the same way throughout. These curves show that if the tube is operated at a bias voltage near the center of the quadratic region, a voltage considerably in excess of the quadratic limita-

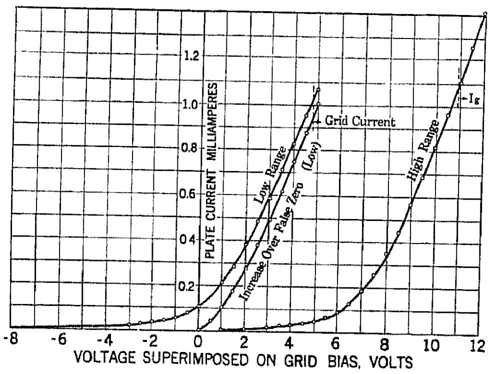

FIG. 14—STATIC CHARACTERISTICS OF VACUUM TUBE VOLTMETER

tion may be applied without wave-form error. Thus the 16-volt r. m. s. curve shows no error when operated at -20 volts bias although the peak of the wave is approximately 23 volts and exceeds the limit of quadratic variation by eight volts.

Fig. 14 shows the $I_p - E_g$ curves for the voltmeter described herein. The wave-form error throughout the low-range was found to be negligible for any of the wave-forms studied, despite the fact that the departure from quadratic variation is quite marked. It is only when the normal bias voltage is considerably in excess of that for which the plate current vanishes, that *slight* differences in wave-form are manifested by different readings in plate current. The plate current then depends solely on that portion of the voltage wave which projects beyond the vanishing point, and any hump or tip on the wave which might be insignificant compared to the entire wave is strongly instrumental in affecting the plate current.

Too much emphasis should not be placed on the elimination of wave-form error. The mere fact that a voltmeter reads r. m. s. volts independently of wave-form does not, of course, permit the indiscriminate use of any wave-form. In fact, in some instances, it might be desirable to use a voltmeter which would, by reversing terminals, detect an unsymmetrical wave-form.

Although the two-range voltmeter described herein is not capable of wave-form error elimination, its usefulness is not necessarily impaired. It does, however, on the higher range tend to *exaggerate* differences in wave-form. In passing, it may be said that this exaggeration is greater, according to the authors' beliefs, in the grid stopping condenser type of voltmeter than in the plate detection type. In fact, the former partakes largely of the characteristics of a *peak* voltmeter.

Of the six features of the vacuum tube voltmeter which were set down at the outset, the following may be said in summary concerning the two-range type studied by the authors:

1. Frequency has but little effect on the operation and this effect can be eliminated by the use of the by-passing condenser,
2. The input impedance is high, of the order of several megohms, and the power factor is low,
3. Differences in wave-form are exaggerated but not, for commercial wave-forms, objectionably so,
4. The senstivity is higher, perhaps, than that of most other communication-frequency measuring instruments. On the instrument designed by the authors, changes of 0.01 volt on the low end of the range, and changes of 0.05 volt on the high end are readily detectable,
5. The range is inherently low, covering, probably, a band of voltages from a tenth or a few tenths of a volt to about 10 volts,
6. The stability of calibration over the entire life of the tube is questionable. Experiment showed, however, that in general the calibration could be expected to remain constant for periods of operation of over 40 hr.

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Discussion

J. P. Barton: The vacuum-tube voltmeter as applied to the communication industry today, as Mr. Jansky has pointed out, is certainly an outstanding means of measurement on circuits where no current is to be absorbed by the measuring instrument.

The vacuum-tube voltmeter is very versatile in creating a means of measuring constants of circuits which was not possible several years ago by the older means common to power work in the measuring of currents and voltages.

One of the big advantages, as has been pointed out, is in the wave-form errors which do exist and which can be eliminated by using the quadratic portion of the static characteristic curve of the tube. From personal experience in the use of vacuum-tube voltmeters in measuring and comparing inductances against standards of inductance, it is very necessary to watch out for the effect of a bad wave form. To keep the wave-form error to a minimum or zero, it is best to make the impedance and phase angles equal for both the known and unknown inductances, and to present the same potential side of each impedance to the grid of the vacuum-tube meter. By this means very accurate comparisons are possible and it offers a quick means of calibration of the inductance.

The Influence of Residual Air and Moisture
In Impregnated Paper Insulation

BY J. B. WHITEHEAD[1]
Fellow, A. I. E. E.
and F. HAMBURGER, JR.[2]
Associate, A. I. E. E.

Synopsis.—*The paper describes experiments in study of the separate influence of residual air and moisture in impregnated paper as used for the insulation of high voltage cables.*

Some sixty similar samples are prepared, dried, evacuated, and impregnated under the same program, except as regards the pressure of evacuation and impregnation. In groups of three, the samples were evacuated at various absolute pressures between 2 mm. and 76 cm. Hg.

The samples were brass tubes 2.54 cm. in diameter, 122 cm. long with 25 layers of wood pulp paper applied in the usual lapping spirals. Each sample was equipped with outside test and guard electrodes.

Throughout their entire history, i. e., before and after impregnation, observations were made on the samples of their dielectric absorption and their final conductivity. These studies have led to the conclusions as to the influence of moisture.

After impregnation, the samples are studied as to power-factor and dielectric loss over the range of electric stress 20 to 300 volts per mil, and of temperature 20 deg. cent. to 80 deg. cent. These studies have led, principally, to the conclusions of the influence of residual air. They show clearly the importance of thorough impregnation, and the conditions under which it may be accomplished. The causes of rising power-factor—voltage curves and methods of avoidance are clearly indicated.

The principal results and conclusions are given at the end of the paper.

THE sharp rise in the power-factor—voltage curve of impregnated paper insulation, such as found in high-voltage cables, is commonly attributed to the ionization of entrapped air or gases. The present investigation was undertaken with a view to studying the influence of different amounts of entrapped air in such insulation. The general plan adopted was to construct a large number of samples as nearly identical as possible, to impregnate them under similar conditions, except as regards the air pressure, and to follow the electrical behavior of the samples as closely as possible throughout their entire history. In addition to the results of the study of the influence of entrained air, other interesting data on impregnated paper insulation have also been obtained.

THE TEST SAMPLES

Each test sample consisted of a brass tube 2.54 cm. (1 in.) in diameter and 121.9 cm. (4 ft.) long. Each tube was cleaned and polished and then received its wrapping of cable paper. The wood pulp paper furnished by a prominent manufacturer, was 0.01016 cm. (0.004 in.) thick, and 2.54 cm. (1 in.) wide. The tube was put in a lathe and a leather friction grip mounted on the carriage of the lathe fed the paper on to the tube spirally in the usual manner. In each layer the successive turns lapped slightly, the lap varying from 0.08 cm. (1/32 in.) down to a close butt contact. The laps or joints in successive layers were displaced successively by approximately 0.635 cm. (¼ in.). The tension on the paper during wrapping was between 3.5 and 5 lb. The greater number of samples were wrapped with 25 layers of paper, a few having 40 layers. At each end of the paper wrapping additional layers built up the thickness to twice that over the body of the sample. These ends were secured with a wrapping of linen thread.

Each sample was provided with a test electrode of sheet lead 0.04 cm. (1/64 in.) thick, and 71.12 cm. (28 in.) long placed equidistant from the two ends. Guard electrodes 5.08 cm. (2 in.) wide were mounted on either end of the test electrodes. The electrodes were cut from sheet lead, carefully smoothed out and wrapped on in single pieces with a longitudinal opening of about 0.08 cm. (1/32 in.) at the butt joint. The

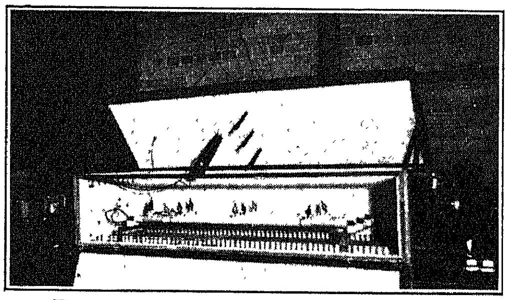

FIG. 1—SPECIMENS IN DRYING BOX

electrodes were firmly held in place and in close contact with the paper by a continuous band of linen thread wound over the outside. Fig. 1 shows a finished view of the samples before impregnation.

There were 60 test samples in all, divided into 20 groups of three each. The three samples in each group received the same treatment throughout. The treatment of the several groups differed only as regards the air pressure at which impregnation took place.

THE DRYING CHAMBER

The drying chamber consisted of a wooden box 182.9 cm. (6 ft.) long, 60.9 cm. (2 ft.) wide, and 45.72 cm. (18 in.) deep, with hinged top and front. The box was lined throughout with sheet asbestos. The bottom of the box was completely covered

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with a grid of bare resistance wire mounted zigzag on small porcelain insulators. Subdivision of this wire into several circuits provided an electric heater readily adjustable for any desired temperature. A view of the interior of the drying chamber is seen in Fig. 1. The specimens, three in a group, were supported on porcelain insulators several inches above the heater wire. A slow draft of air was drawn through the box continuously by means of a small rotary fan and holes in the two ends of the box. The equipment also included three resistance thermometers, which fitted snugly into the interiors of the brass tubes forming the central conductors of the samples, reaching to about their central portions. A thermostat with relay connection operating on the heater circuits permitted maintaining the box at uniform temperature over long periods of time. Bakelite micarta bushings in the top of the box permitted introduction of 1500 volts, direct current, to the central conductor of each sample and connections to the test electrodes, thus permitting study of the volt-ampere characteristics of the insulation throughout the period of drying.

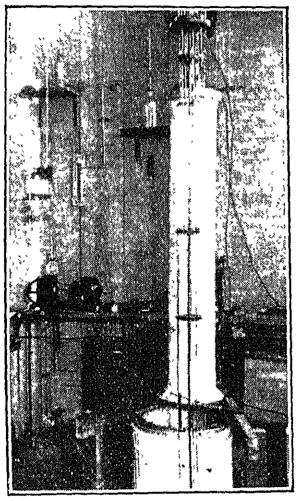

Fig. 2—Evacuating and Impregnating Equipment

Impregnating Chamber

The impregnating chamber consisted of a steel tube of 12.7 cm. (5 in.) inside diameter, 213.4 cm. (7 ft.) long, 0.32 cm. (0.125 in.) wall thickness. The tube was placed in vertical position (see Fig. 2) and the test samples lowered into it by means of a special rack. Both top and bottom of the tube were equipped with special steel flanges. That at the bottom was slotted so as to completely close the end of the tube, except for a 0.635-cm. (¼-in.) pipe opening in the center. The flange at the top had a carefully machined surface on which could be sealed an outside plate providing the necessary air tight joint. The top and bottom flanges and all pipe connections were carefully brazed to the tube. Over the lower 152.4 cm. (5 ft.) of the tube there were wound two circuits of resistance wire mounted on wooden strips, providing means for heating the impregnating chamber. A galvanized iron casing was built around this lower portion of the tube. The jacket so made was filled with transformer oil, completely covering the heating coils. The outside surface of this oil jacket was enclosed in pipe covering and asbestos cement as heat insulation. The upper portion—about 60.96 cm. (2 ft.) of the steel tube—was wrapped with ten turns of 0.318 cm. (1/8-in.) copper tubing through which water was passed continuously. The purpose of this feature was to maintain the top flange at relatively low temperature in order that a wax seal might be used for closing the impregnating chamber. This afforded a convenient and rapid method for handling the necessarily frequent opening and resealing of the impregnating chamber. The evacuating system consisted of a motor driven oil immersed vacuum pump, connected with the impregnating chamber through a system of glass tubing which included calcium chloride or other type of drying chamber, a vacuum gage, a trap for receiving any compound which might go over into the vacuum system, and the usual stop-cocks which also provided for the admission of dry air. The vacuum gage was of the usual manometer type, permitting a minimum reading of one mm. Hg., which was the lowest pressure used. The connection to the vacuum system was near the top of the impregnating chamber.

Immediately below the bottom of the impregnating tube there was placed a 10-gal. tank in which the compound was heated preparatory to impregnation. This tank was surrounded by an outer oil jacket which contained electric heating circuits, the whole being covered outside with heat-insulating material. The pipe connection to the bottom of the impregnating chamber extended to the bottom of the compound tank and was equipped at its lower end with a special high grade valve operated from above the level of the compound.

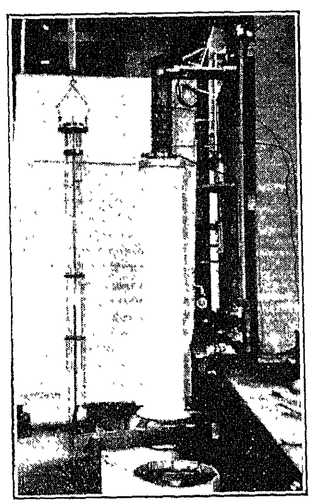

Fig. 3—Impregnating Rack and Tank

For impregnation, the specimens were mounted on a

special rack built around a 1.27-cm. (½-in.) square brass rod (see Fig. 3). This rod carried three wooden supports into which the three specimens fitted in triangular arrangement. Near the top of the rod there was mounted a bakelite terminal block through which there passed 9 small glass tubes. These tubes extended down through the wooden supports and carried test leads to the electrodes and to three resistance thermometers which were inserted in the central tubes of the three specimens. The central conductor or tube of each specimen was connected to the main brass rod of the rack which constituted the high-voltage terminal for absorption and conductivity measurements. Each

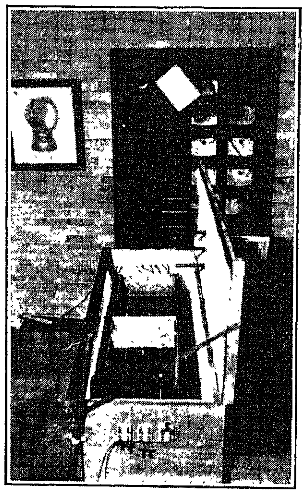

FIG. 4—HIGH-VOLTAGE TEST BOX

of the glass tubes terminated just above the bakelite terminal block and was fitted with a small brass cup connected to the lead passing through the tube. The cups were filled with mercury, receiving platinum wires which, in their turn, were sealed into glass tubes mounted in the brass plate which finally closed the top of the impregnating tube. This plate was about 17.78 cm. (7 in.) in diameter and 1.27 cm. (½ in.) thick. The rack carrying the specimens was suspended under the center of this brass plate by three brass studs passing through the bakelite terminal block. The three samples could thus be mounted in the rack, the 10 necessary electrical connections promptly made, and the whole lowered into the impregnating chamber. The brass plate rested on the top flange of the impregnating chamber to which it could be rapidly sealed with ordinary laboratory wax. By this arrangement electrical measurements were possible during the period of impregnation and cooling. An additional oil encased heating bath was provided so that the 4-gal. can, in which the compound was received from the manufacturer, could be heated before opening. The compound was never exposed to the air except at high temperature, and then only for the period necessary to adjust to final temperature in the impregnating reservoir.

HIGH-VOLTAGE TEST BOX

The high-voltage test chamber consisted of a wooden box approximately 182.88 cm. (6 ft.) long and 60.96 cm. (2 ft.) wide and 35.56 cm. (14 in.) deep, with hinged front and top (see Fig. 4). The box was lined throughout with sheet asbestos. It contained two galvanized iron troughs, one inside the other, the space between being filled with transformer oil heated by submerged electric circuits. The specimens were mounted on porcelain supports placed on the bottom of the inner trough, which was then filled with the compound in which the specimens had been impregnated. Occasional measurements were taken with no compound in this tank. Lying longitudinally in the bottom of the tank and between the specimens were three resistance thermometers placed so that they would read the temperature of the compound in close proximity to the center of each specimen. Pipe connections in the bottoms of the tanks permitted ready removal of the compound and the oil of the heating bath.

The high-voltage connections were made through bushings made of micarta tubes filled with impregnating compound. These were mounted in the top of the box at one end, connection being made to the central tubes of the specimens by tight fitting plugs. Connections

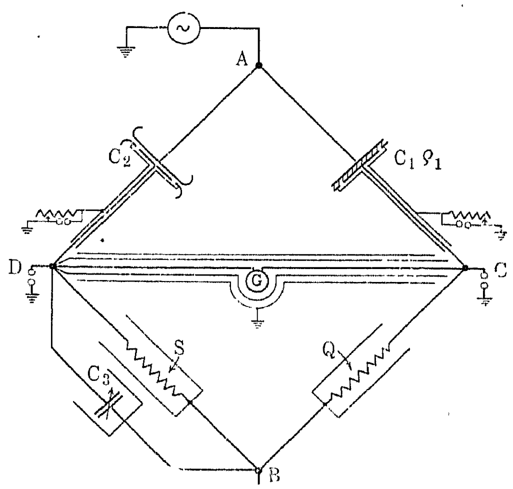

FIG. 5—SCHERING BRIDGE WITH ELECTROSTATIC SCREENING

to the test electrodes were also brought out through micarta bushings near the center of the top of the box. Baffle plates and ground shields were so located in the inner trough that the test electrodes of the specimens were completely screened, not only from electrostatic high-voltage influence, but also from any possible leakage due to conductivity in the compound forming the bath. These plates and screens, together with the troughs holding the specimens, were connected electrically to the guard electrodes and all were insulated from ground, the final connection to ground being made through adjustable resistances to be described in a later paragraph.

High-Voltage Measuring Equipment

The source of alternating voltage was a 5-kw., single-phase, 125-volt, 60-cycle, motor-driven generator having a smooth wave. The motor-generator set was driven from a large storage battery and provision was made for close frequency and voltage control from the observer's position. The voltage was stepped up by means of a 10-kv-a. transformer of ratio 115 to 34500 volts. The accurate determination of voltage on the high-voltage side was made with a two circuit screened potential divider permanently connected across the high-voltage side of the transformer. Each circuit of this potential divider had a resistance of 1.6 megohms and it thus constituted a moderate steadying load on the generator. The voltage was computed from the current as measured in the ground side of one of the resistance circuits.

The method of measurement of power factor was a modified form of Schering bridge. A schematic diagram of connections is shown in Fig. 5. As is well known this method requires an air condenser in one arm of the high-voltage side. The low arms of the bridge are resistances, one arm being shunted by an adjustable air condenser by means of which final balance is obtained. When the bridge is balanced, the following relations exist:

$$\zeta_1 = \frac{C_3}{C_2} Q \; ; \; C_1 = \frac{S}{Q} C_2 \qquad (1)$$

Whence, power factor $\simeq$ tan (phase difference)

$$= \omega C_1 \zeta_1 = \omega S C_3 \qquad (2)$$

Preliminary measurements with a cylindrical high-voltage air condenser of 8.26×10^{-11} farad capacity indicated that for a close balance of the bridge the values of the capacity in the two high arms of the bridge should not differ by a ratio of more than 3 or 4. In view of this fact it was found desirable to construct an air condenser to meet the range of capacities to be found in the samples to be measured. An illustration of the condenser as finally constructed is shown in Fig. 6. It is of parallel plate type having a single central high-voltage plate, 182.88 cm. by 243.84 cm. (6 ft. by 8 ft.), and two low-voltage plates, each 121.92 cm. by 182.88 cm. (4 ft. by 6 ft.), one placed on either side the high-voltage plate. Each low-voltage plate was surrounded by a guard plate 22.86 cm. (9 in.) wide. All metal surfaces were of 0.0396-cm. (0.0156-in.) soft copper, mounted on oak frames, with smooth flat joints, and with edges turned back as indicated in Fig. 6. The low-voltage plates were supported each from its guard plate by six bakelite blocks. The guard plates in their turn were supported by steel rods hung from the upper part of the supporting wooden structure. The entire low-voltage system of each plate was adjustable horizontally permitting a maximum spacing between low-voltage and high-voltage plates of 25.4 cm. (10 in.). The lowest value of spacing used in the experiments was 5.08 cm. (2 in.), thus corresponding to a total range of capacity using both plates of 77×10^{-11} farad to 15.4×10^{-11} farad. The outside surfaces of the low-voltage plates were screened with copper gauze connected to the guard plates. A 2.54-cm. (1-in.) diameter brass tube extended from the rear of each low voltage plate to the observer's position some 609.6 cm. (20 ft.) away. This tube was also connected to the copper gauze and guard plate. The connections to the low-voltage plates of the condenser were carried through these tubes. The screening system so formed was connected to ground through an adjustable resistance connection, and insulated from ground at all other points. (See Fig. 5.)

The resistances used in the two low arms of the bridge were of Curtis type; that is, specially wound for freedom from capacity and inductance. Each box was placed in its own metal case connected to earth. The resistances used in grounding the various guard circuits were of high grade laboratory type.

The charging currents of the specimens were measured in the ground connections from the test electrodes by means of a Dolacelek quadrant electrometer shunted with resistance and calibrated for voltage in terms of laboratory standards. Suitable switching was arranged so that this electrometer could be used for measuring the current in any section of the bridge connection, including the guard ring circuits of the air condenser, those of the test specimens, and that in the potential divider for measuring the high voltage.

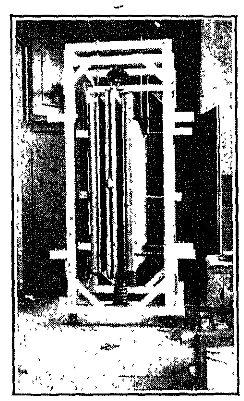

Fig. 6—High-Voltage Air Condenser

The detecting instrument for balance of the bridge was a Rubens vibration galvanometer with a sensitivity of 6.6×10^{-6} amperes per millimeter division in an eyepiece at one meter distance. In the present experiments the instrument was 304.8 cm. (10 ft.) from the observer. The blurring of the sharp image of an incandescent filament indicated unbalance, and it is certain that a much higher sensitivity was reached. No effort was made to estimate a numerical figure for sensitivity of this instrument. Under the best conditions of observation a variation of 0.1 per cent of the adjustable air condenser was sufficient to upset the setting. This

variation corresponds to a difference of one figure in the 5th place of a power factor 0.00746. The sensitivity falls off towards the lower range of voltage gradients and lower temperatures, owing to the low values of the loss component of the current. We estimate that in the lowest range of our observations the maximum error in our observations of loss and power factor is not greater than 2 per cent of the values as given.

At a distance 457.2 cm. (15 ft.) beyond the galvanometer and in the same line of vision was mounted a vibrating reed frequency meter with magnified scale having two reeds per cycle. This arrangement, together with close speed control, permitted accurate adjustment of the frequency to the natural period of the vibration galvanometer.

The adjustable air condenser for the final balance of the bridge was of the usual dial type with interleaved plates, one set rotating about a vertical axis, and its position being indicated by a pointer moving over a 180 deg. scale on the top. It was placed in a grounded metal box. This condenser was calibrated in place with its leads and with the guard circuits connected as

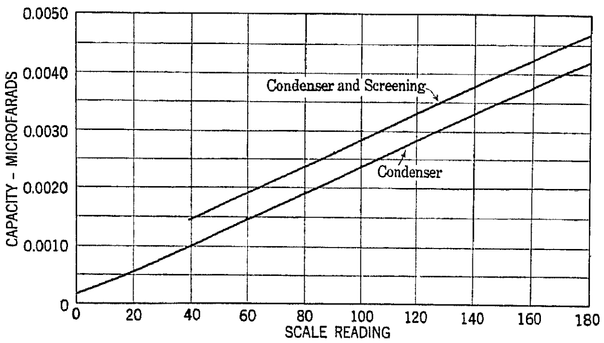

Fig. 7—Calibration Curve of Condenser and Screening

in Fig. 5, by the Maxwell-Thompson method. The calibration curve is shown in Fig. 7.

Mention has been made that the guard rings of both air condenser and test specimen were connected to earth through adjustable resistances. Reference to the diagram of connections, Fig. 5, will indicate the points at which these connections to earth were made. It will be noted that the guard principle was applied to the entire length of the connections from the central electrodes to the center of the bridge by running them in tubes connected to the guard electrodes, and to the rear screen of the central electrodes. The importance of electrostatic screening in work of this character is well understood. We also discovered very early in the tests that it is important that the screening systems and also the guard rings be maintained at the same voltage above ground as that of the central or test electrodes. This was readily accomplished by measuring the currents to earth from test electrodes and from guard rings separately. Then on balancing the bridge a resistance of suitable value could be inserted in the ground connection of the guard ring system. In general not more than two adjustments were necessary to obtain the correct values. In the final condition of balance the resistance in the bridge arm and the resistance to ground in the guard circuit, have values inversely as their respective currents to ground. We believe that in measurements of this character sufficient attention has not been given to the possibilities of stray fields at the ends of or over the leads to the test electrode. In our observations we frequently found that a resistance of several thousand ohms to ground would be necessary in our guard circuit, and that a change of 2 per cent or 3 per cent in the total value of this resistance would be sufficient to throw the bridge out of balance.

Program of Test

Following is a general statement of the preparation, treatment, and test of the various groups of samples. As a general thing the three samples of one group were carried together through the entire process.

The three samples of each group, equipped with test electrodes and guard electrodes, were first placed in the drying box in which the temperature was slowly raised to 105 deg. cent. A slow draft of air passed through the box. The condition of the samples was observed by absorption and conductivity measurements at 1500 continuous volts. The samples remained in the drying box until there was no further change in their electrical characteristics over a period of twenty-four hours. As a rule this required a total elapsed time of about seventy-two hours. The samples were then transferred while hot to a rack and immediately lowered into the impregnating chamber already heated to 105 deg. cent. The chamber was then sealed, the vacuum pump started, and the pressure reduced to that at which the samples were to be impregnated. In certain cases the pressure was reduced to a minimum of between 1 to 2 mm. Hg. absolute pressure and afterwards allowed to rise to the value for impregnation. The impregnating chamber was kept at the desired pressure and at 105 deg. cent. for two hours and then left to stand over night; usually about fifteen hours. The pressure was readjusted next morning to the proper value and the temperature allowed to fall to 80 deg. cent. The compound already heated to the same temperature was then slowly admitted to the impregnating chamber, the air pressure being maintained approximately constant. After the samples were completely immersed the temperature was maintained for two hours at 80 deg. cent. the pressure remaining unchanged. Air was then admitted to the impregnating chamber and absorption and conductivity measurements made on the samples at atmospheric pressure and 80 deg. cent. The chamber was then allowed to cool over night and the absorption and conductivity measurement repeated at atmospheric pressure and room temperature.

The impregnating chamber was then heated to about 45 deg. cent., the compound drained, and the samples quickly transferred to the high-voltage test box. During this transfer the specimens were in the open air for about five minutes. In the high-voltage test box the samples were immersed in compound. The compound was completely changed for each two groups of samples, three-quarters of the compound being removed for each group, and the fresh compound being that in which the group had been impregnated. In the high-voltage box, measurements were made of total dielectric loss, power factor, and charging current, over a range of temperature from that of the atmosphere to 80 deg. cent., and over a range of voltage of 1.5 to 30 kv., corresponding generally to the range 15 to 300 volts per mil. Usually all three samples were measured in parallel with occasional check measurements on single samples to insure that they were of uniform characteristics.

Following the power measurements, the samples were dipped in paraffin and set aside for further possible tests.

TABLE I

P. F. MEASUREMENTS. SPECIMENS 3A, 3B, 3C

Pri. E Ratio 300-1	Q	S	Cond. rdg.	C_3	Power factor	W.	Temp. air	Deg. cent. spec.	Specimens
40	2000	5379.5	76.5	0.002325	0.004710	0.6145	20.8	28.1	3A and 3B and 3C
60	2000	5374.0	76.0	0.002315	0.004695	1.379	20.5	27.6	3A and 3B and 3C
80	2000	5367.0	76.2	0.002320	0.004700	2.474	20.8	27.6	3A and 3B and 3C
100	2000	5359.0	78.5	0.002365	0.004790	4.210	21.4	27.6	3A and 3B and 3C
90	2000	5361.0	78.0	0.002355	0.004760	3.345	21.4	27.6	3A and 3B and 3C
20	2000	5371.0	76.0	0.002315	0.004690	0.151	21.5	27.5	3A and 3B and 3C
10	2000	5371.0	75.5	0.002300	0.004660	0.0376	21.5	27.5	3A and 3B and 3C
60	2000	5365.5	76.5	0.002325	0.004705	1.382	21.5	27.5	3A and 3B and 3C
40	2000	5368.5	76.0	0.002315	0.004690	0.6110	21.4	27.5	3A and 3B and 3C
60	4000	3534.5	122.5	0.00338	0.004500	0.4070	21.5	27.5	3A
60	4000	3565.0	130.0	0.00355	0.004775	0.4330	21.6	27.3	3B
60	4000	3630.0	126.0	0.00346	0.004740	0.4380	21.2	27.0	3C

Typical Observations and Check of Method

The essential measurement is that of power factor, and our measurement of this quantity is based on the final relation of Formula (2); that is to say, the balance of the bridge determines the resistance Q, the setting and capacity of the adjustable air condenser C_3, and also the value of the resistance S in shunt therewith. All of the observations were taken at a frequency of 60 cycles for which value the generator speed could be closely adjusted at each setting, as checked by the amplitude of oscillation of the Hartman and Braun vibrating reed frequency meter. Table I gives a typical set of observations.

The various columns of Table I in their order give the following quantities: The voltage at the low-tension terminals; the resistances of the two low voltage arms of the bridge; the reading of the adjustable air condenser; the corresponding value of the capacity C_3; the power factor as computed from Formula (2); the total loss as computed from the power factor, the current, and the voltage on the specimen; the temperatures of the outside air and inside the test specimen; and finally, the combination of specimens on which the readings were taken. All measurements were made with a two-circuit, shielded, potential divider connected from high voltage to ground. The value of the high voltage was determined by the current in one circuit of this potential divider, and was at all times found to correspond accurately with the ratio of transformation of the transformer (1-300). The order of the readings in Table I, and the repetition of the readings at different voltages indicates the constancy with which readings are repeated, and also that the three specimens of a single group possess characteristics which are closely similar.

Table II is a sample of the measurements which must be made of the currents in the test and guard circuits of both high-voltage condenser and specimen, at each value of voltage. These readings fix the values of the resistances which must be inserted in the ground connections of the guard circuits in the final condition of balance.

The accuracy of the method was tested by inserting

TABLE II

CURRENT MEASUREMENTS. SPECIMENS 3A, 3B, 3C

Pri. E	$R_1{}^1$	Zero	Rdg.	Dfln.	I	Circuit
40	400	1.58	6.05	4.47	10.85×10^{-3}	Tail circuit 3 spec. in parallel
	1600	1.58	4.42	2.84	2.16×10^{-3}	Guard circuit 3 spec. in parallel
	1000	1.58	5.38	3.80	4.0×10^{-3}	Tail circuit H. V. condenser
	1000	1.58	4.90	3.32	3.75×10^{-3}	Guard circuit H. V. condenser

known values of resistance in series with the test samples. In one case the two halves of the high-voltage air condenser were separated, one-half being placed in either high-voltage arm of the bridge. Under these circumstances the adjustable air condenser and all of its connections had to be removed from the bridge in order to secure a balance which was readily accomplished with resistance only in the low arms. A resistance of 12799 ohms was then connected in the low side lead of the central electrode of one of the two high-voltage condensers C_1 (Fig. 5). The bridge was

then balanced again and the measured value of the power factor was found to be 0.001967. The computed value based on the $I^2 R$ loss in the resistance was 0.001976. Corresponding values using another value (20349 ohms) of series connected resistance were 0.003105 and 0.003140. These constitute a check for values of power factor below the minimum values encountered in our work.

For values in the higher range of power factor a similar series of observations was made using a Moscicki condenser. This condenser is of Leyden jar type immersed in oil and screened against electrostatic influence. The loss in this condenser alone at 12,000 volts was found to be 1.79 watts. With 6003 ohms connected in series the loss was 2.32 watts; the measured difference being 0.53 watts. The computed $I^2 R$ loss in the added resistance was 0.522 watts. A second set of observations at a lower value of voltage gave corresponding figures 0.299 and 0.296 watts. The total power factor in these observations was in the neighborhood of 0.02. This value of power factor is well above most of those encountered in our observations.

The records also show many examples of agreement between the values of loss measured for three samples in parallel and the sum of the values taken on the three

to 1500 volts to the samples while in the drying box, and for measuring both charge and discharge currents to the test electrode in the usual manner. A Weston D'Arsonval galvanometer of sensitivity of 1.5×10^{-10} amperes per division, was used.

The behavior of each group of three samples was

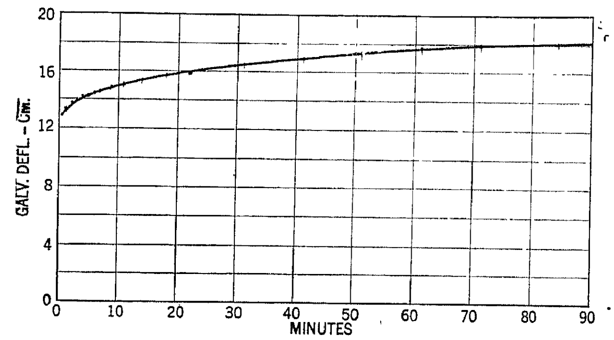

FIG. 8—CHARGING CURVE

Cable paper specimen 1A—110 volts, 20 deg. cent.—Not impregnated

much the same throughout the drying period. Individual samples differed in considerable amount in the initial stage, but the shapes of the current-voltage curves, and the types of changes with temperature showed little or no variation among the various sets.

TABLE III
POWER FACTOR MEASUREMENTS. SPECIMENS 2A, 2B, 2C

Pri. E.	Q	S	Cond. rdg.	C_3 mfd.	Power factor	I	W	Specimens
40	2000	3601.5	131.0	0.00357	0.00485	6.6×10^{-3} amps.	0.384	3 spec. in par.
40	6000	3733	134.5	0.003660	0.005150	2.21×10^{-3}	0.1367	2A
40	6000	3558.5	134.0	0.003640	0.004890	2.15×10^{-3}	0.1261	2B
40	6000	3491	136.0	0.00368	0.004845	2.10×10^{-3}	0.1221	2C
							0.3849	for 3 spec.

samples individually. Table III gives an instance of this.

The computed value of the capacity of the high voltage air condenser with both halves set at 5.08 cm. (2 in.) spacing is 77×10^{-11} farad. The value as determined by the current measured at 15,000 volts in the test electrode circuit on the ground side was 78.4×10^{-11} farad. The value of this capacity is needed only for computations of the capacity of the specimens. The latter value was used in these computations.

EXPERIMENTAL OBSERVATIONS

The Influence of Moisture in Cable Paper. We discuss first the influence of different amounts of absorbed moisture on the electrical properties of unimpregnated cable paper. The fact that each set of test samples had to be carefully dried out under exactly similar conditions afforded easy opportunity for studying the progressive change in the absorption and final resistance at different stages throughout the drying period. Provision was made for applying continuous voltage up

The following description and curves refer to test sample 1-A.

The three samples of group 1, equipped with paper

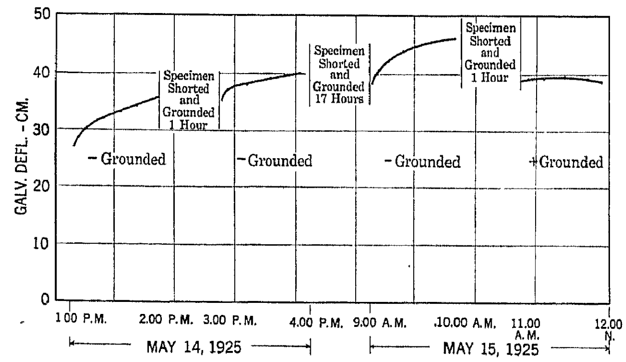

FIG. 9—CHARGING CURVES

Cable paper specimen 1A—110 volts—22.5 to 25.0 deg. cent.—Not impregnated

and electrodes, were dried and tested in the impregnating chamber. On test sample 1-A the current through the insulation to the test electrode at 110 volts con-

tinuous, and at 20 deg. cent. was as shown in Fig. 8. The current rises continuously for an hour and a half after the first application of voltage, and is not yet constant. After discharging and charging a second time at the same temperature the second curve begins abruptly at approximately the value at which the first curve left off. Much the same effect is observed for a further period of short circuit and charge. After reversal of polarity the current starts at a lower value and seems to decrease slowly. (See Fig. 9.) These results indicate that the continuous application of voltage gives a progressive increase in conductivity, and therefore shows the conspicuous presence of the well-known Evershed effect. All three samples in the group give approximately the same shape of curves, but their ordinates differ amongst themselves. At

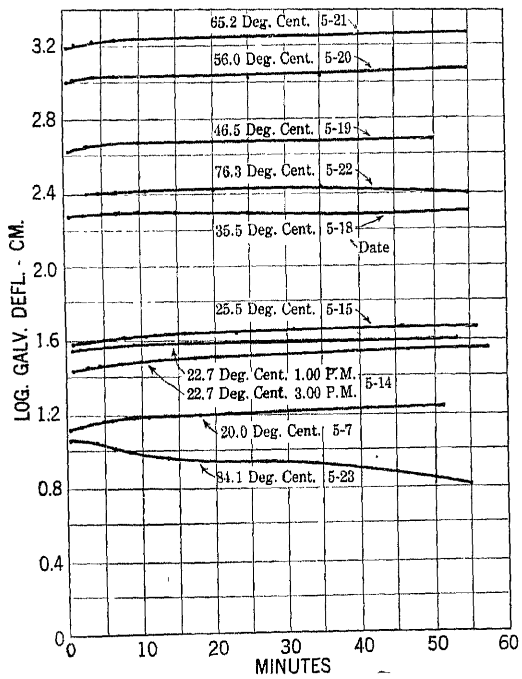

FIG. 10—CURRENT—TIME CURVES

Cable paper specimen 1A—At various temperatures and 120 volts d-c Not impregnated

this temperature (20 deg. cent.) there is only an extremely small indication of residual charge for any of the samples the 30-sec. reading on discharge for 1-A being 5-mm. galvanometer deflection, which may be compared with the corresponding deflection of 40 cm. on charge.

The temperature of the samples was then raised in steps of approximately 10 deg. cent. and allowed to come to a steady electrical state at each temperature. The changes in the electrical characteristics follow very closely the changes in temperature. During the process of temperature change it is easily possible to follow the change in the value of the charging current (see Fig. 13). Up to 65 deg. cent. there is a steady and rapid increase of the values of the currents, the curves, however, tending to become flatter (see Figs. 10 and 11). The value of the residual charge also increases through this range, the 30-sec. value reaching 9.2 centimeters at 55 deg. cent. It is still very small as compared with the charging current at the corresponding interval and absorption is as yet not great enough to show itself in the form of the charging current curve. The samples were allowed to stand over night at 75 deg. cent. It was

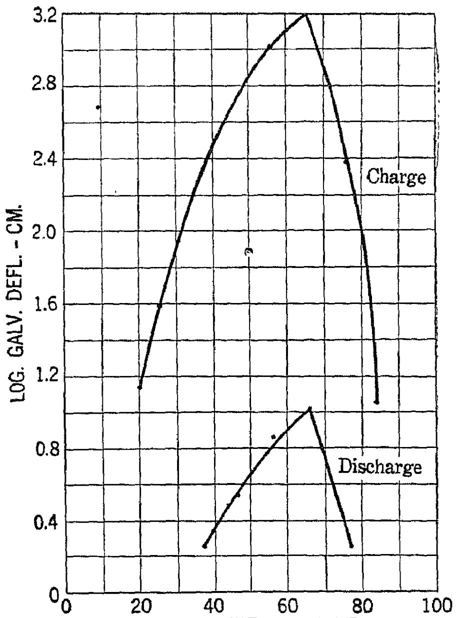

FIG. 11—CHARGE AND DISCHARGE CURRENTS AT INCREASING TEMPERATURE. UNIMPREGNATED PAPER

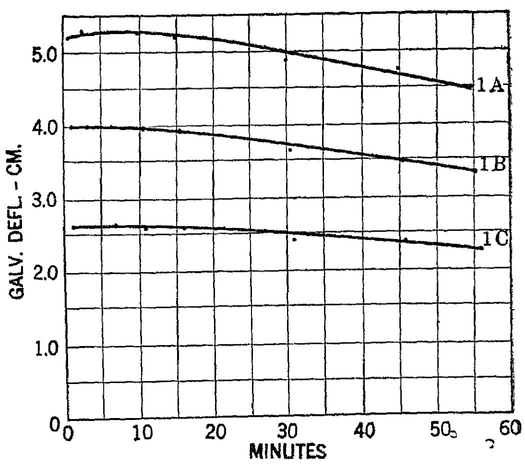

FIG. 12—CHARGING CURVES

Cable paper specimens 1A, 1B and 1C—110 volts, 86.5 deg. cent. Not impregnated

then found that the charging current curve was nearly flat and considerably below that at 65 deg. cent. Thus in this temperature region time enters as a factor. Somewhere between 65 deg. cent. and 75 deg. cent. the conductivity of the sample stops rising and decreases (see Fig. 11). The curve of current on discharge is also correspondingly lower, thus indicating a relation between

absorption and moisture content. It should be noted, however, that the absorption is of negligible magnitude as compared with conduction, up to 75 deg. cent.

At 85 deg. cent. the charging current curves rise slightly at the beginning and then fall off (see Fig. 12). They are still quite flat, but the decrease, although slow, seems to indicate that absorption begins to play its part in the shape of the curve. After standing over

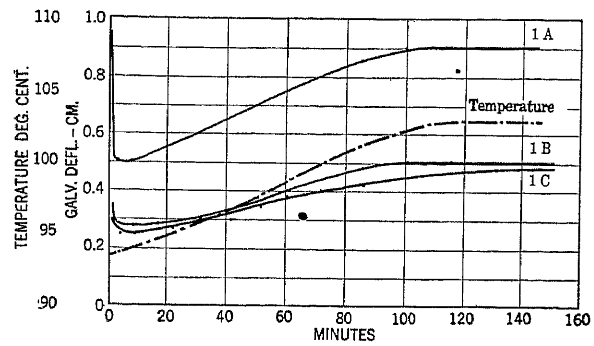

Fig. 13—Charging Curves Cable Paper Specimens 1A, 1B, and 1C with Increasing Temperature—93.5 to 103.0 Deg. Cent.—1500 Volts. Not Impregnated

night at 90 deg. cent. the initial rise in the charging current curve disappears and a typical absorption curve takes its place. In this condition, however, the paper is still extremely sensitive to temperature change. For example, starting at 94 deg. cent. the initial limb of the absorption curve is readily observed but as the temperature is gradually raised to 103 deg. cent. over a period of two and one-half hours, the current is seen (Fig. 13) to rise and become steady contemporaneously with the temperature. For temperatures above 104 deg. cent.

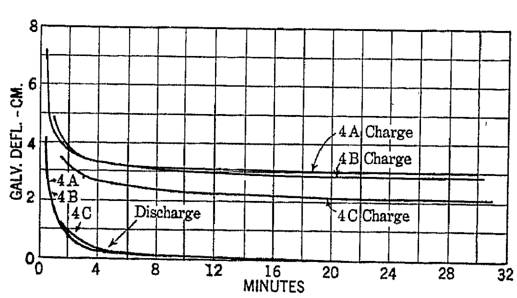

Fig. 14—Charge and Discharge Curves—Cable Paper Specimens 4A, 4B, and 4C—1500 Volts—110.6 Deg. Cent. Not Impregnated

the curves are all of typical absorption type, (see Fig. 14) with little change in shape up to 125 deg. cent. Both absorption and final conductivity continue to decrease in this range suggesting the continued elimination of moisture. Above 85 deg. cent. measurements were made at 500 volts, 1200 volts, and 1500 volts continuous. In all cases, the galvanometer gave deflections in proportion to the voltage and all the curves repeated their shapes.

The general conclusion from these studies is that the paper contains large amounts of moisture which are driven off rapidly at 75 deg. cent. or above. Up to this point its conductivity masks the usual dielectric properties. At 105 deg. cent. the paper seems to reach a fairly

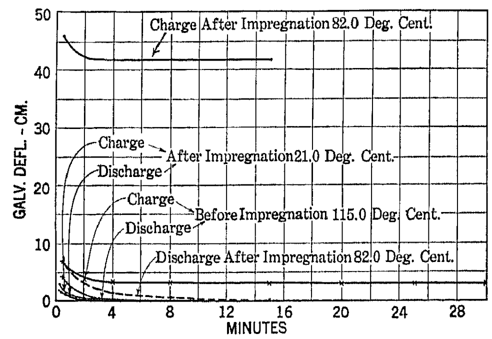

Fig. 15—Charge and Discharge Curves—Cable Paper Specimen 4A—1500 Volts. Before and After Impregnation

definite condition. It appears as a dielectric having marked absorption and relatively high resistivity. On further elevation of temperature more moisture is driven off with consequent improvement of dielectric properties, although the changes are neither as marked

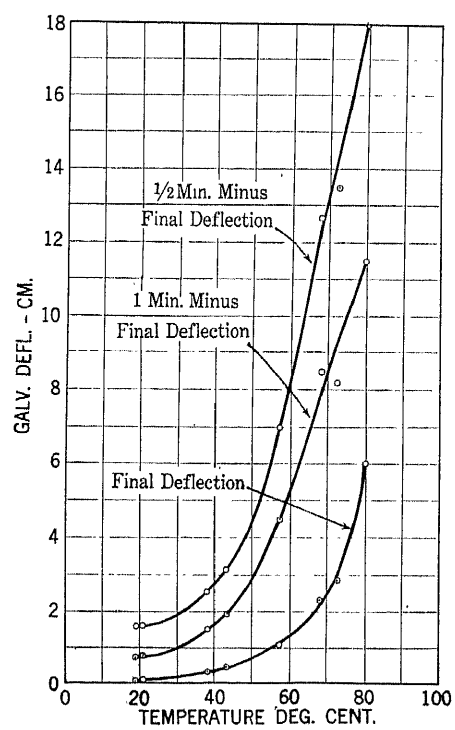

Fig. 16—Absorption and Conductivity—Temperature after Impregnation—Specimens 3B and 3C In Parallel

nor as rapid as in the earlier stages. The properties are quite definite at any one temperature, although there are differences of from 50 to 100 per cent as amongst successive samples tested. Characteristic curves of one group at a temperature of 110.6 deg. cent. are shown in Fig. 14. The final current of specimen

4-C indicates a resistivity of 1.23×10^{-15} ohms per cm.[3]

Influence of Impregnation on Absorption Characteristics. In preparing the samples for impregnation they were maintained at a temperature of 105 deg. cent. in the drying chamber until they reached a steady state as regards absorption and conduction. Immediately after impregnation at 80 deg. cent. the absorption current values were found to have increased from 40 to 70 times depending upon the sample, although the relative positions

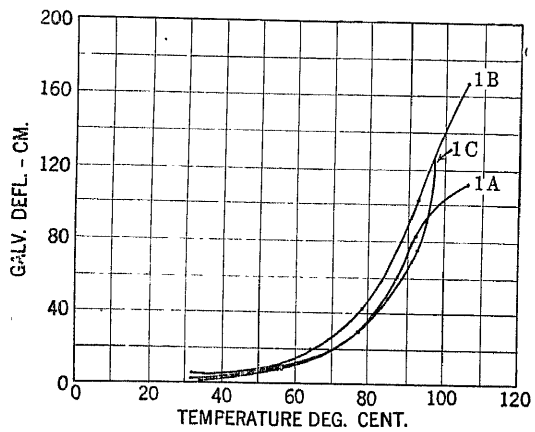

FIG. 17—CHARGING CURRENT—TEMPERATURE AFTER IMPREGNATION. FINAL DEFLECTION

of the three curves of the samples of each set remained about the same. The condition is shown in Fig. 15. In this case the increase in absorption current after impregnation is only about 14 times. This is due to the lower temperature (82 deg. cent.) at which the measurements were taken after impregnation. These increases in absorption and in conductivity decrease slowly with time if the sample is maintained at high temperature.

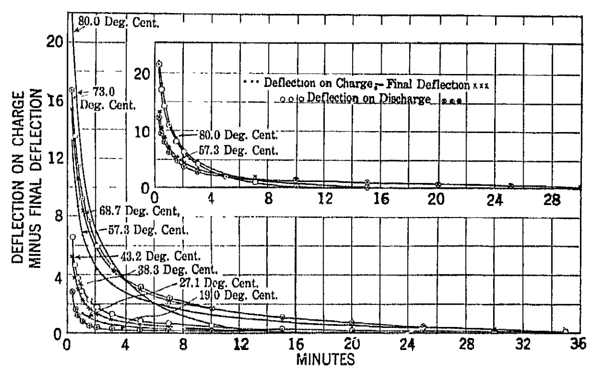

FIG. 18—ABSORPTION—CABLE PAPER SPECIMENS 3A, 3B, AND 3C—IN PARALLEL—AFTER IMPREGNATION—1500 VOLTS

There is also some evidence that the application of alternating voltage causes further reductions. The samples apparently reach a uniform condition after one or two days of test. These changes offer an interesting problem for future study.

This large increase in the charging current is almost entirely due to the increased conductivity of the sample, resulting from its impregnation. Figs. 16 and 17 show the rapid increase of both the final and the one minute galvanometer deflections with increasing temperature taken on the samples after impregnation. Obviously the final deflections are measures of the conduction current, and it will be seen that the one-half and the one minute deflections increase at much the same rate. Furthermore, the residual charge, as indicated by the discharge curves, shows relatively a much smaller increase than the conduction current. This is shown in Fig. 15 in which the discharge curve after impregnation and at 82 deg. cent. is seen to lie only slightly higher than the curve for 21 deg. cent. before impregnation. Fig. 18 shows for various temperatures the difference between the final steady deflection and the deflection taken at intervals during the charging period. These curves therefore show the total current minus the

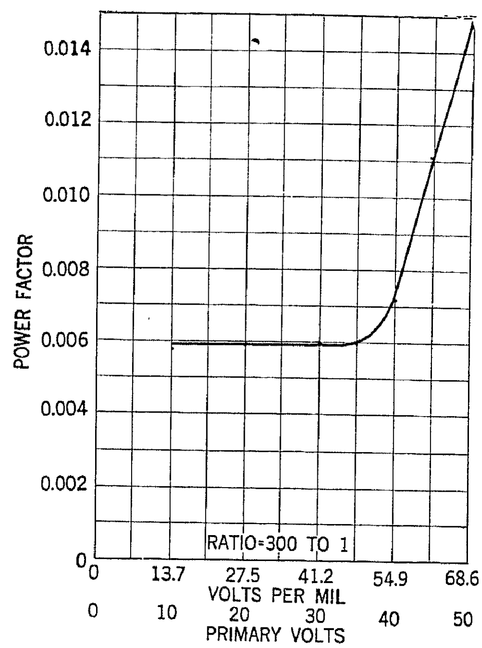

FIG. 19—POWER-FACTOR—VOLTAGE CURVE—COMMERCIAL CABLE "A"—4000-VOLT, THREE-CONDUCTOR, NO. 6

4/32 in. by 3/32 in. insulation—measured in air on 4 ft. of cable—21.5 deg. cent.

conduction current that is to say, the so-called reversible anomalous current. It will be seen that with the exception of the curve at 80 deg. cent. the absorption increases with the temperature throughout. The inset on Fig. 18 compares the reversible anomalous current on charge with the current on discharge, for temperatures 80 deg. cent. and 57 deg. cent. It will be seen that at each temperature the two curves are closely coincident which again indicates that the large increase in the charging current curves after impregnation is due to the increased conductivity caused by the presence of impregnating material. Moreover, this seems to be a uniform conductivity as that portion of the charging current curve due to absorption is completely reversible.

The conclusion from these observations is that the conductivity of cable paper is greatly increased on

impregnation. There is also a corresponding increase in the dielectric absorption. The increased conductivity falls off rapidly with the temperature and at 20 deg. cent. approaches that of the dry unimpregnated paper. The conductivity thus introduced by the compound seems to be constant in character at any one temperature and to possess the irreversible character often observed in liquid dielectrics. A further study is planned of the characteristics of paper and compound separately and in combination, under different conditions of impregation.

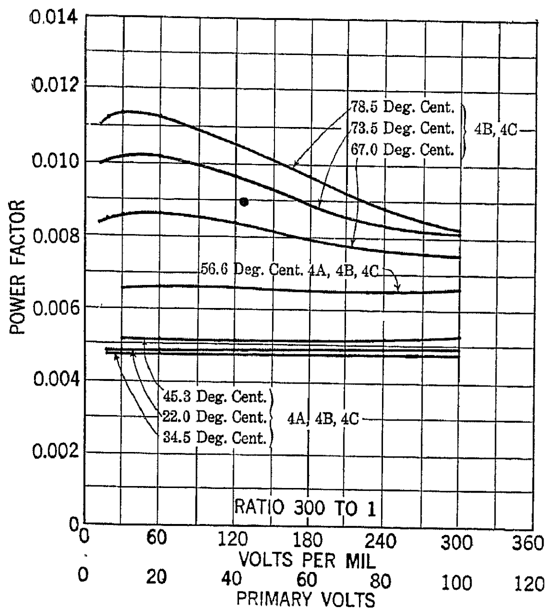

FIG. 20—POWER-FACTOR—VOLTAGE CURVES—SPECIMENS 4A, 4B, AND 4C—IN PARALLEL

Conductor diameter = 1 in. Insulation = 0.10 in. wall, impregnated at 2-mm. pressure

Conductivity in dried state = 4A—3.40 cm.
4B—3.45 cm.
4C—2.55 cm.

The Influence of the Air Pressure at Impregnation. The first purpose of our experiments has been the study of the influence of the air pressure at which impregnation takes place, on the shape of the power-factor—voltage curve. The sharp break often observed in this curve, (as for example in Fig. 19), is generally attributed to the presence of air in thin layers which breaks down to cause increased loss, when the voltage gradient rises above a certain value. It does not appear to be clearly determined, however, whether or not these air layers are generally distributed through the successive layers of paper. If so a variation of the air pressure at which impregnation takes place might have an influence on the shape of the power-factor curve. It may be said here that the evidence from our experiments indicates that the break in the power-factor curve is far more often to be traced to a definite air layer between insulation and a loose fitting sheath, rather than to air films distributed through the body of the insulation.

The air pressure at impregnation apparently plays a more important role in its action in facilitating the driving off of still further residual moisture, after the greater part has been driven off under preliminary temperature drying. It appears to be impossible to completely expel all moisture from cable paper. Final temperature and air pressure, and the time during which they are applied are the principal factors determining the ultimate state of the paper. Extending the ranges of these factors well beyond the values used in cable manufacture we have had no difficulty in obtaining power-factor—voltage curves which appear greatly superior to those encountered in cables as manufactured. We have obtained these results by methods of drying, evacuating, and impregnating which certainly are more careful and prolonged than those to be observed in many cable factories. On the other hand none of the methods we have used involves special difficulty, and with one possible exception, that of the method of obtaining a tight fitting sheath, it appears that it should be possible to approximate them in the factory production of cables. They would, however, entail more complex equipment than that commonly used, and more time, thus increasing costs considerably. One manufacturer has stated that he can duplicate our flat power-factor curves in cables for the market if the purchaser will stand for the additional price.

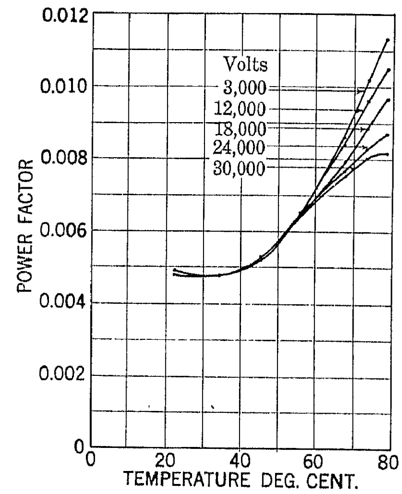

FIG. 21—POWER FACTOR—TEMPERATURE CURVES—SPECIMENS 4A, 4B, AND 4C IN PARALLEL

Conductor diameter = 1 in. Insulation = 0.10 in. wall, impregnated at 2-mm. pressure

The results of our study of the influence of the air pressure at impregnation are shown in the series of curves of Fig. 20 to 38. The range of pressure studied is from 2 mm. to 76 cm. Hg. absolute pressure, extending well beyond the range used in manufacture, in both directions.

There are several striking results to be noted from this series of curves:

Characteristics of Thorough Impregnation. The char-

acteristic type of the power-factor–voltage curve for complete impregnation is exemplified in Fig. 20 for 2 mm. impregnating pressure. Up to 56 deg. cent. the power-factor curves are perfectly flat over the range range. Although the values of the power factor may vary from one set of curves to another this typical shape is remarkably well preserved over the range of pressure 2 mm. to 10 cm.

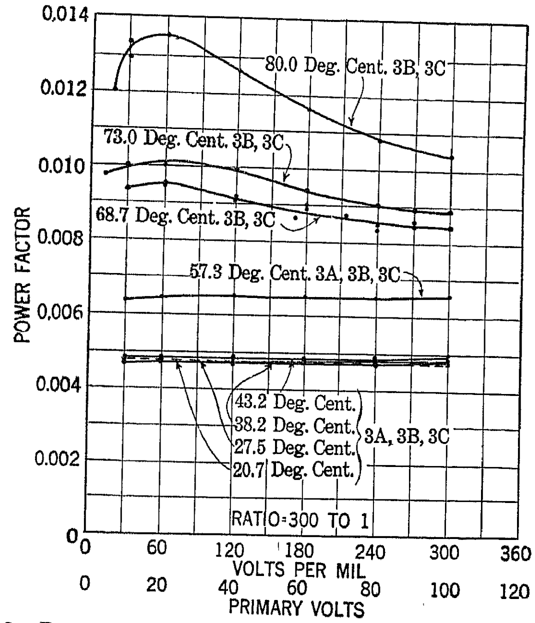

FIG. 22—POWER-FACTOR—VOLTAGE CURVES—SPECIMENS 3A, 3B, AND 3C IN PARALLEL

Conductor diameter = 1 in. Insulation —0.10 in. wall, impregnated at 5-mm. pressure
Conductivity in dried state = 3A—0.65 cm.
3B—0.63 cm.
3C—0.57 cm.

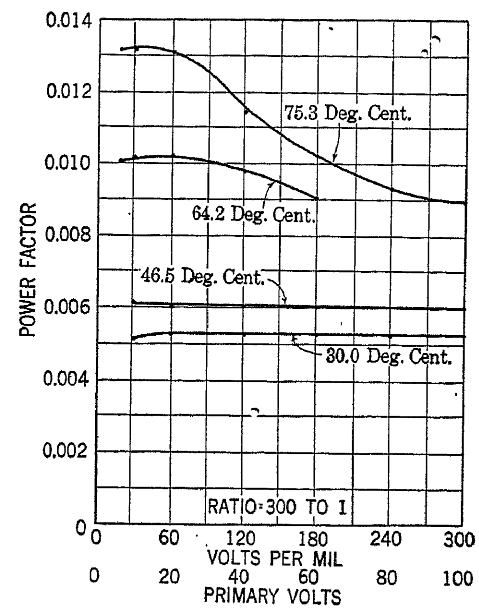

FIG. 24—POWER-FACTOR—VOLTAGE CURVES—SPECIMENS 12A, 12B, AND 12C IN PARALLEL

Conductor diameter = 1-in. Insulation = 0.10 in. wall, evacuated and impregnated at 1-cm. pressure
Conductivity of dried specimens about twice normal due to high humidity
Conductivity in dried state = 12A—8.3 cm.
12B—8.1 cm.
12C—6.8 cm.

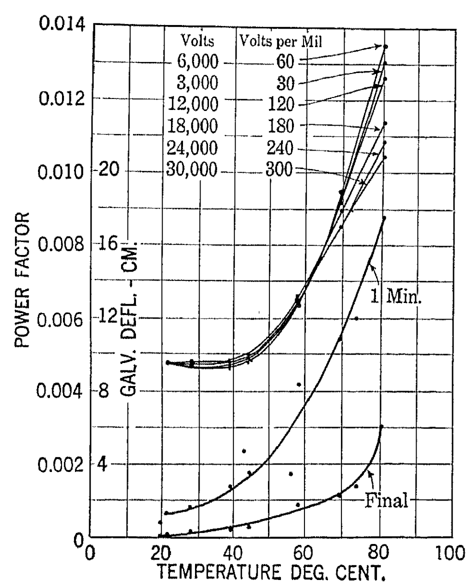

FIG. 23—POWER FACTOR—TEMPERATURE CURVES—SPECIMENS 3A, 3B, AND 3C IN PARALLEL

Conductor diameter = 1 in. Insulation = 0.10 in. wall, impregnated at 5-mm. pressure

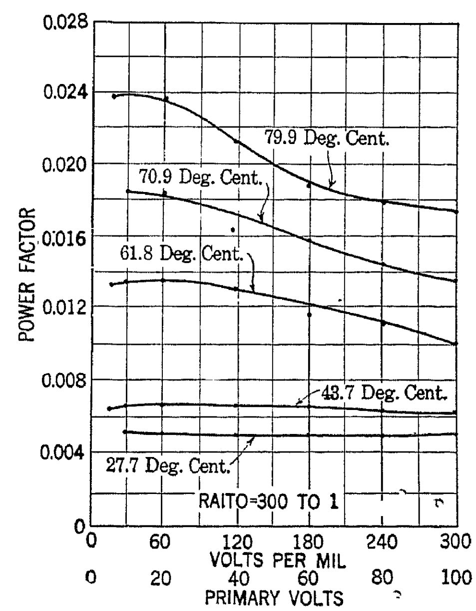

FIG. 25—POWER-FACTOR—VOLTAGE CURVES—SPECIMENS 10A, 10B AND 10C IN PARALLEL

Conductor diameter 1-in. Insulation = 0.10 in. wall, evacuated and impregnated at two-cm. pressure
Conductivity of dried specimens about six times normal due to high humidity
Conductivity in dried state = 10A—19.0 cm.
10B—20.0 cm.
10C—16.0 cm.

30 to 300 volts per mil. At higher temperatures the curves show increasing maxima in the neighborhood of the relatively low gradient 40 volts per mil and apparently tending to become flat towards the upper

Pressure Range for Thorough Impregnation. Over the range of pressure 2 mm. to 10 cm. Hg. pressure the flat power factor curve of the lower range of temperature appears throughout. There is no evidence within

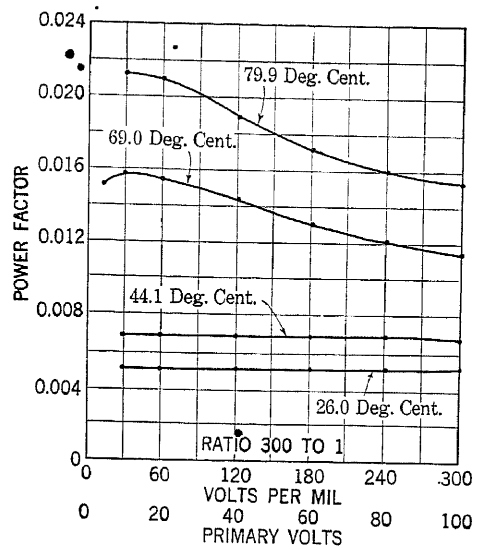

Fig. 26—Power-Factor—Voltage Curves—Specimens 11A, 11B, and 11C in Parallel

Conductor diameter = 1.0-in. Insulation 0.10-in. wall, evacuated and impregnated at 3 cm. pressure
Conductivity of dried specimens about three times normal due to high humidity
Conductivity in dried state = 11A—8.7 cm.
11B—4.6 cm.
11C—6.2 cm.

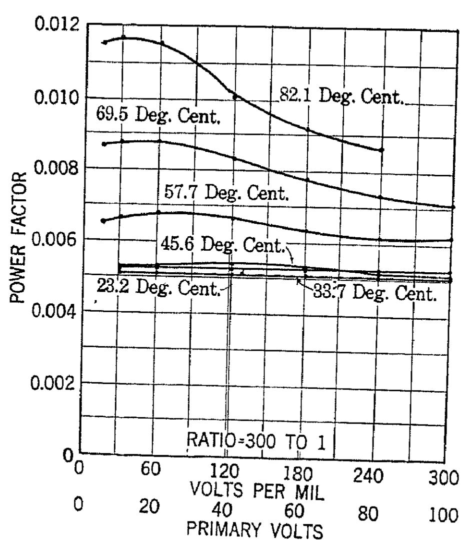

Fig. 27—Power-Factor—Voltage Curves—Specimens 8A, 8B, and 8C in Parallel

Conductor diameter = 1-in. Insulation = 0.10 in. wall, evacuated to 2-mm. pressure
Impregnated at 5-cm. pressure
Conductivity in dried state = 8A—4.00 cm.
8B—2.70 cm.
8C—1.80 cm.

the range of air pressures mentioned of a break followed by sharply rising values in the power-factor–voltage curve. This seems to indicate that with sufficient care to obtain thorough drying, impregnation, and close fitting sheath, internal gaseous ionization may be eliminated and good power factor curves obtained without

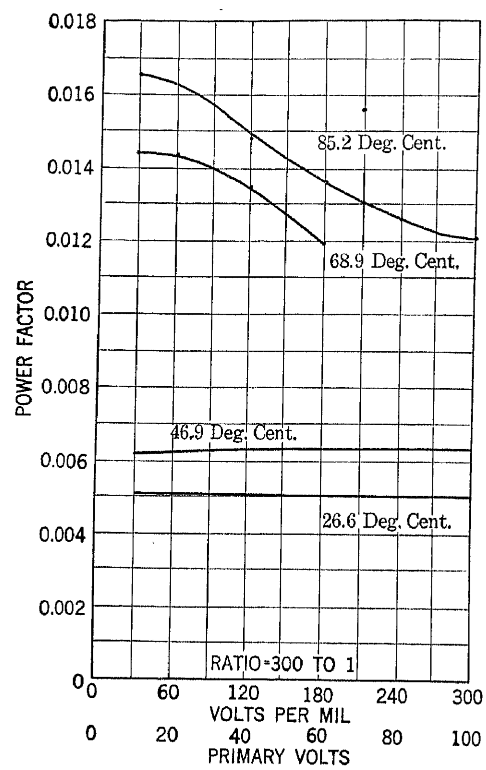

Fig. 28—Power-Factor—Voltage Curves—Specimens 14A, 14B, and 14C in Parallel

Conductor diameter = 1-in. Insulation 0.10-in. wall, evacuated and impregnated at 5-cm. pressure
Conductivity in dried state = 14A—2.30 cm.
14B—1.75 cm.
14C—1.35 cm.

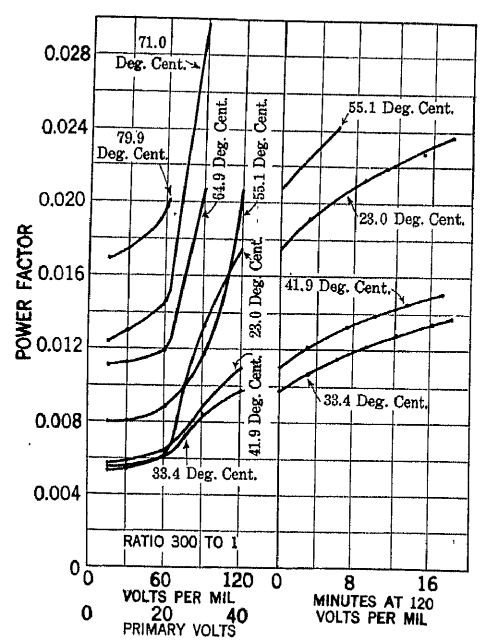

Fig. 29—Power-Factor—Voltage—Power Factor—Time—Specimen 6A

Conductor diameter = 1-in. Insulation 0.10-in. wall, impregnated at 5-cm. Hg.
Conductivity in dried state—3.35 cm.

the necessity of an evacuation pressure lower than 10 cm. Hg. Or stated more briefly, complete impregnation of cable paper, without resulting gaseous ionization, or rising power-factor–voltage curve, may be obtained at air pressures of impregnation up to 10 cm. Hg.

A single exception to the foregoing is illustrated by Fig. 29, giving results on a set of specimens evacuated and impregnated at 5-cm. pressure. This set of curves

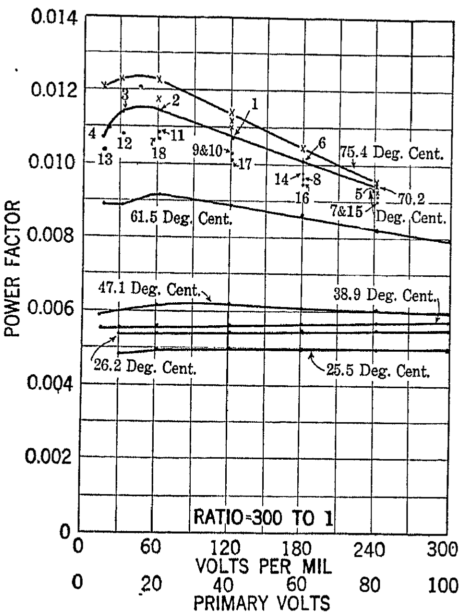

FIG. 30—POWER-FACTOR—VOLTAGE CURVES—SPECIMENS 9A, 9B, AND 9C

Evacuated to 3-mm. pressure
Impregnated at 10-cm. pressure
Numbers at points indicate order in which they were taken
Conductivity in dried state = 9A—3.95 cm.
9B—3.95 cm.
9C—2.55 cm

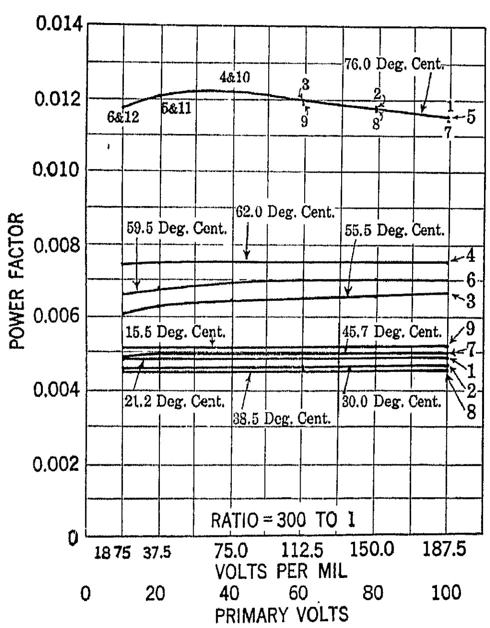

FIG. 31—POWER-FACTOR—VOLTAGE CURVES—SPECIMENS 2A, 2B, AND 2C IN PARALLEL

Conductor diameter = 1 in. Insulation, 0.16-in. wall.
Evacuated to 3.5-cm. pressure
Impregnated at 10-cm. pressure
Drying period abnormally long
Numbers at curves indicate the order in which they were taken
Conductivity in dried state = 2A—2.05 cm.
2B—1.22 cm.
2C—1.42 cm.

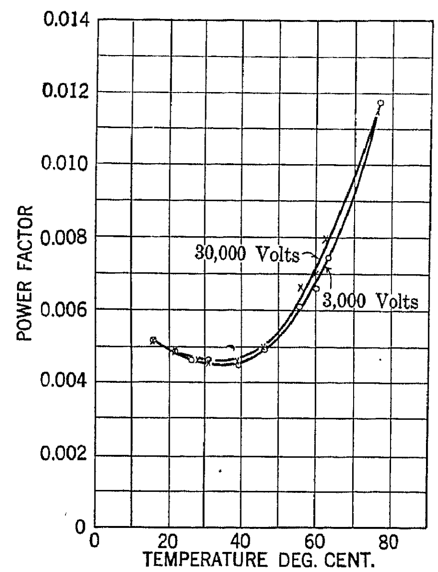

FIG. 32—POWER-FACTOR—TEMPERATURE CURVES—SPECIMENS 2A, 2B, AND 2C IN PARALLEL

Conductor diameter = 1 in. Insulation, 0.16-in. wall

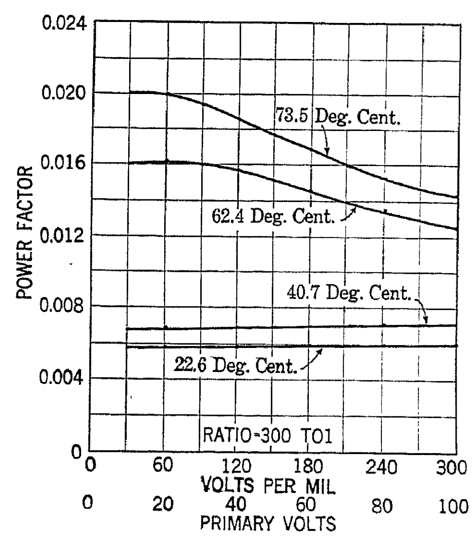

FIG. 33—POWER-FACTOR—VOLTAGE CURVES—SPECIMENS 13A, 13B, AND 13C IN PARALLEL

Conductor diameter = 1-in. Insulation, = 0.10-in. wall
Evacuated and impregnated at 10-cm. pressure
Conductivity in dried state = 13A—3.60 cm.
Drying period—192 hrs. 13B—3.85 cm.
13C—3.25 cm.

shows the typical ionization power factor curve; *i. e.*, a sharp break followed by rapidly ascending values. These curves were taken in a series of studies with ascending values of impregnation pressure. At first they seemed to indicate that a critical pressure causing

internal ionization had been reached. On going to higher pressures, however, the normal flat curves were again observed. Another set of specimens was therefore constructed, dried, evacuated, and impregnated under the same conditions as those of set No. 6 shown in Fig. 29. The results of this duplicate set No. 14 are shown in Fig. 28 and as will be noted they indicate perfectly flat curves at lower temperatures and other

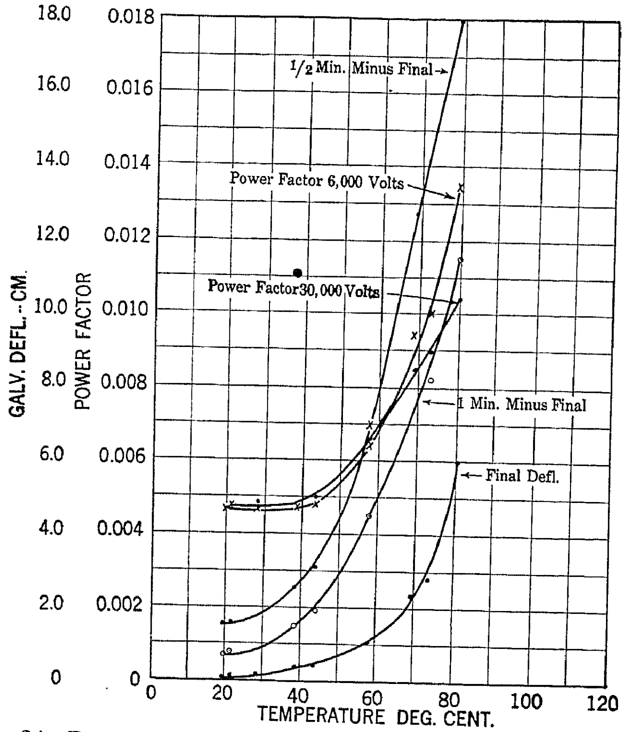

FIG. 34—POWER FACTOR AND ABSORPTION—TEMPERATURE—SPECIMENS 3B AND 3C

Conductor diameter = 1-in. Insulation = 0.10-in. wall
Evacuated and impregnated at 5-mm. pressure

characteristic features of normal curves. The curves of Fig. 28 should also be compared with those of Fig. 27 in which the impregnation also took place at 5-cm. pressure. In this case, however, the specimens had received a preliminary evacuation pressure of 2 mm. This treatment extracted more residual moisture which resulted in lower values of power factor as compared with those of Fig. 28. Following these results further observations were made in set No. 6, a period of several months having elapsed. The specimens were found to still possess their original characteristics as shown in Fig. 29. It is evident, therefore, that in the sharp difference of behavior of these two sets prepared apparently in the same manner, we should find very direct evidence as to the cause of the ascending power-factor curve. In a subsequent series of accelerated life tests the specimens of set No. 6 all showed much shorter life than those of set No. 14. In stripping the specimens those of set No. 6 were found to contain large amounts of entrained air between layers, while those of set No. 14 were almost devoid of traces of air. We conclude, therefore, that for some reason which we can not explain, perhaps for example, the priming of the compound, this set of specimens did not receive complete impregnation. No other instance of this difficulty was encountered.

Internal Gaseous Ionization. Above an evacuation and impregnation pressure of 10 cm. the power-factor curves begin to change their characteristic shape. This is exemplified in Figs. 35 to 38 inclusive, for pressures 15, 25, 40, and 76 cm. respectively. The curves at low temperatures begin to lose their horizontal character and the curves at higher temperatures instead of decreasing with increasing voltage gradient now show the characteristic sharp upward turn, due to the ionization of the internal air spaces. Within this region there is also evidence that the degree of impregnation changes over a considerable period of time. This is illustrated in the curves of Fig. 36. The order in which the curves

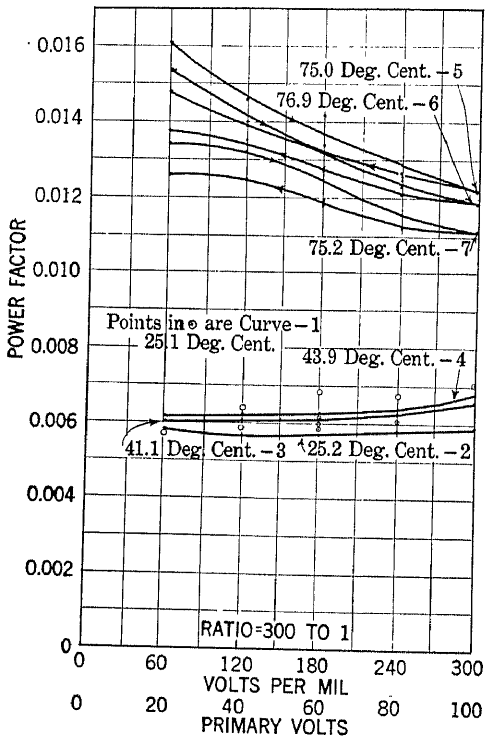

FIG. 35—POWER-FACTOR—VOLTAGE CURVES—SPECIMENS 19A, 19B, AND 19C IN PARALLEL

Conductor diameter = 1 in. Insulation, 0.10-in. wall
Evacuated and impregnated at 15 cm. pressure
Conductivity in dried state = 19A—2.00 cm.
19B—1.50 cm.
19C—3.60 cm.

are taken is indicated and clearly shows that a temperature cycle results in a change of internal condition. This period seems to extend over several days, after which time there is some suggestion that the specimens reach a steady and improved condition. Some of the specimens in this range have been stripped and all show the presence of copious air spaces.

We show elsewhere that a layer of air between insulation and sheath is a very probable cause of gaseous

ionization. It may be seen, therefore, that even with thorough impregnation of the insulation, gaseous ionization may still exist between the insulation and sheath and reflect itself in the characteristic upward break in the power-factor—voltage curve.

Influence of Residual Moisture. Although as already noted the power-factor—voltage curves have a typical shape for all pressures, up to 10 cm., it will be observed that some of the specimens show very much higher values of power factor than others, as for example, sets Nos. 11 and 13, Figs. 26 and 33. These differences are apparently due to excess amounts of residual moisture. As stated in the earlier part of the paper a definite program of drying and evacuation was determined and followed, with the idea that it would bring all the specimens to the same initial condition. A quite different result was found. Table 4 gives the drying period and temperatures of the various specimens together with, in columns 4, 5, and 6 the values of their final conductivities after drying, this latter being expressed in terms of galvanometer deflections. The wide range of variation is at once evident. It is chiefly caused by the variation in the atmospheric humidity. In the drying period the specimens are heated in the presence of a slow draft of air, as already described. At very high values of atmospheric humidity, during the summer months, it was impossible even in prolonged periods of drying to reduce the conductivity below the very high values indicated by specimens Nos. 10, 11, and 12. The curves of specimens Nos. 10, 11, and 12 especially seem to indicate that residual moisture will cause higher values of power factor without materially changing the shape of the curve. If, however, the pressure is carried down sufficiently low, say to 1 cm. Hg., this may offset the imperfect drying conditions and

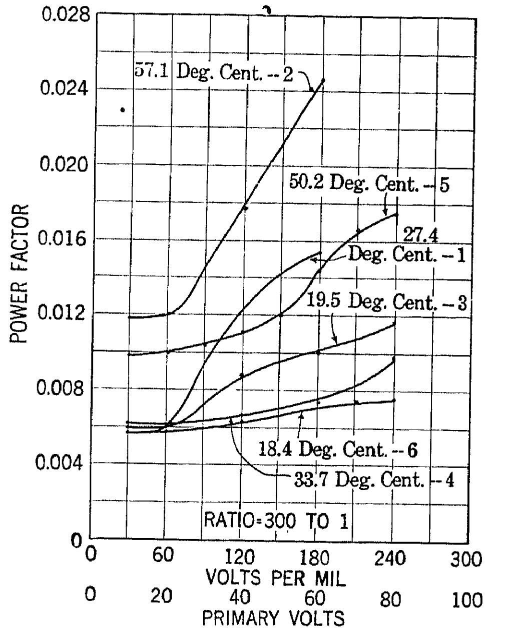

FIG. 36—POWER-FACTOR—VOLTAGE CURVES—SPECIMENS 17A, 17B, AND 17C IN PARALLEL

Conductor diameter = 1 in. Insulation = 0.10-in. wall
Evacuated and impregnated at 25-cm. pressure
Conductivity in dried state = 17A—2.25 cm.
17B—1.60 cm.
17C—1.55 cm.

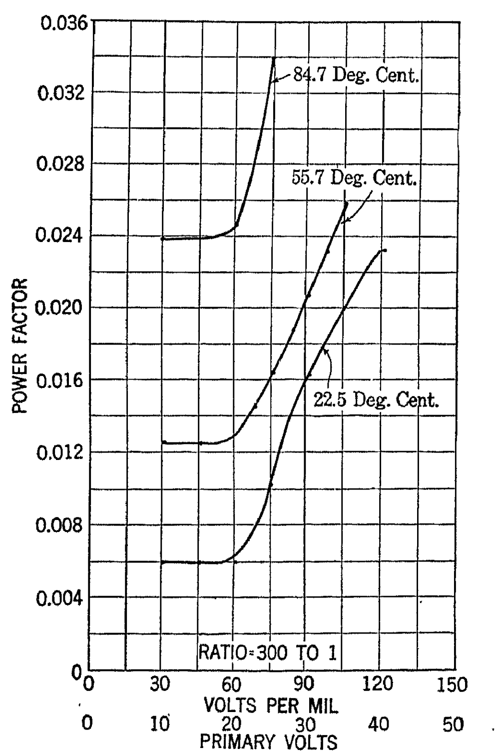

FIG. 37—POWER-FACTOR—VOLTAGE CURVES—SPECIMENS 16A, 16B, AND 16C IN PARALLEL

Conductor diameter = 1 in. Insulation, 0.10-in. wall
Evacuated and impregnated at 40-cm. pressure
Conductivity in dried state = 16A—3.15 cm.
16B—2.85 cm.
16C—2.10 cm.

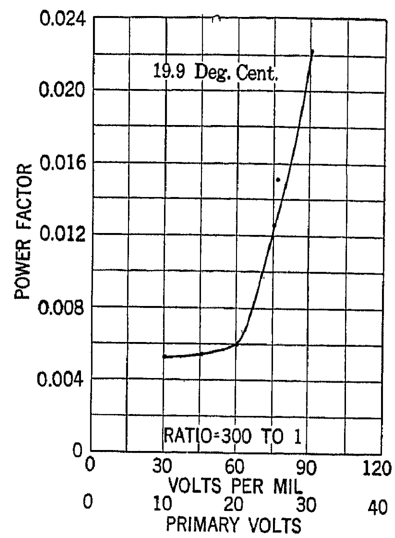

FIG. 38—POWER-FACTOR—VOLTAGE CURVES—SPECIMENS 15A, 15B, AND 15C IN PARALLEL

Conductor diameter = 1 in. Insulation, = 0.10-in. wall
Evacuated and impregnated at 76-cm. pressure
Conductivity in dried state = 15A—1.95 cm.
15B—3.25 cm.
15C—4.25 cm.

result in a power-factor curve of normal shape and value. It appears evident that our preliminary drying period—72 hours at 105 deg. cent. in a slow draft of air at atmospheric pressure,—is very thorough. The subsequent treatment as regards evacuation has relatively small influence up to 10-cm. evacuation pressure. The power-factor–voltage curves all retain their shape. Such differences as appear are principally in the absolute values of power factor at the higher temperatures. These increases are always to be explained either by high atmospheric humidity or higher values of pressure at evacuation. These increases in power factor never assumed serious proportions. For example, as regards pressure of evacuation, the difference between 2 mm. and 5 cm. is reflected in an increase of the maximum power-factor from 0.012 to 0.017. At 10-cm. evacuation the power factor is of the order of 0.02. Another indication of the thoroughness of the preliminary drying was found in a comparison of the absorption of one set of samples taken before evacuation and after evacuation to 4-mm. pressure. The dielectric absorption and residual conductivity was about the same before and after evacuation.

refined laboratory studies that there is an intimate connection between the dielectric loss and dielectric absorption. The curves of Fig. 34 emphasize this relationship in a very striking manner. They suggest that it should be possible to control the losses and power factor in cable insulation by means of studies of the property of absorption of the insulating materials. Such studies may be carried out at moderate values of continuous potential. Work in this direction is now under way by the authors. The decreasing values of power factor with increasing voltage gradients, always found in well impregnated specimens, is of interest in this connection. In our study of absorption we have shown the close importance between the absorption of impregnated paper and the conductivity of impregnating oil. It is known that good liquid dielectrics often evidence a saturation current that has a decreasing conductivity with increasing voltage. It appears probable that in our experiments, the impregnating oil, being liquid at the higher temperatures, possesses this decreasing conductivity with increasing voltage, thus accounting for a lower absorption, lower losses, and lower power factor.

TABLE IV
DRYING AND IMPREGNATION HISTORIES
Sets 2–19

Set no.	Drying data					Impregnation data		
	Time after start of drying	Approx. temp. deg. cent.	Final deflection A	Final deflection B	Final deflection C	Evac. press	Impreg. press	
2	Just before impregnating Drying very long.	102-103	2.05	1.22	1.42	3.5 cm.	10 cm.	
3	96	105	0.65	0.63	0.57	5 mm.	5 mm.	Overheated to 160 deg. for 30 min.
4	72	100	3.40	3.45	2.55	2 mm.	2 mm.	
5	72	106	2.38	2.20	1.65	1 cm.	1 cm.	
6	72	106	3.35	3.00	1.85	5 cm.	5 cm.	
8	72	106	4.00	2.70	1.80	2 mm.	5 cm.	
9	72	105	3.95	3.95	2.55	3 mm.	10 cm.	
12	72		8.30	8.10	6.80	1 cm.	1 cm.	
10	96		19.0	20.0	16.0	2 cm.	2 cm.	Drying data doubtful due to high humidity.
11	72		9.70	4.60	6.20	3 cm.	3 cm.	
13	192	107	3.60	3.85	3.25	10 cm.	10 cm.	
14	72	104	2.30	1.75	1.35	5 cm.	5 cm.	
15	96	104	1.95	3.25	4.25	Atmosphere	45 cm.	
16	72	103	3.15	2.85	2.10	40 cm.	40 cm.	
17	72	103	2.25	1.60	1.55	25 cm.	25 cm.	
19	72	104	2.00	1.50	3.60	15 cm.	15 cm.	

Influence of Absorption and Conductivity. Throughout our measurements, we have taken closely parallel readings of power factor and of conductivity and dielectric absorption at 1500 volts continuous. The curves of Fig. 34 specimens 3-B and 3-C, show the variation with temperature of the power factor, of the final conductivity, and of absorption, as indicated by the one-half minute and one minute readings of the charging current curve. The similarity of form of the power factor and absorption curves is very striking. It has been recognized since the early work of Hopkinson, Rowland, and Hess and from subsequent

Influence of the Closeness of the Fit of the Lead Sheath. One of the striking results of our investigation has been the marked flatness of the power-factor curve at temperatures up to 60 deg. cent., throughout the entire range of voltage gradient 30 to 300 volts per mil, and for specimens impregnated at all air pressures up to 10 cm. Hg. An example of these curves is shown in Fig. 22.

Examples of curves observed on commercial cables having approximately the same type of insulation are shown in Figs. 19 and 39. In looking for possible causes of these marked differences between our specimens

constructed in the laboratory and those taken from cables manufactured by commercial methods, we noticed the relatively loose fit which the sheathing of the commercial cables makes with the underlying cable paper insulation. This condition was perhaps accentuated by the cutting and stripping of the lead

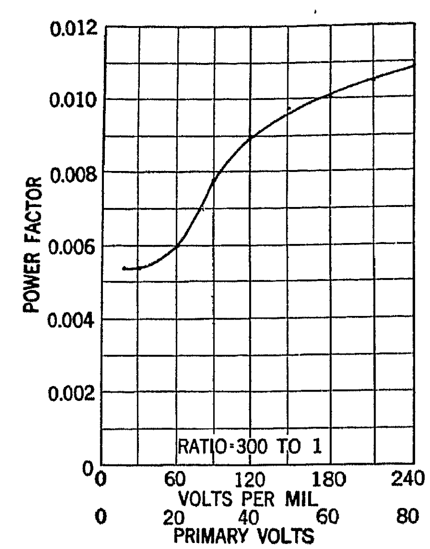

FIG. 39—POWER-FACTOR—VOLTAGE CURVE—COMMERCIAL CABLE "B"—SPECIMENS A, B, C, MEASURED IN PARALLEL IN COMPOUND

500,000 cir. mil conductor
Insulation, 0.10-in. wall—7/8 in. × 0.0065 paper—22.5 deg. cent.

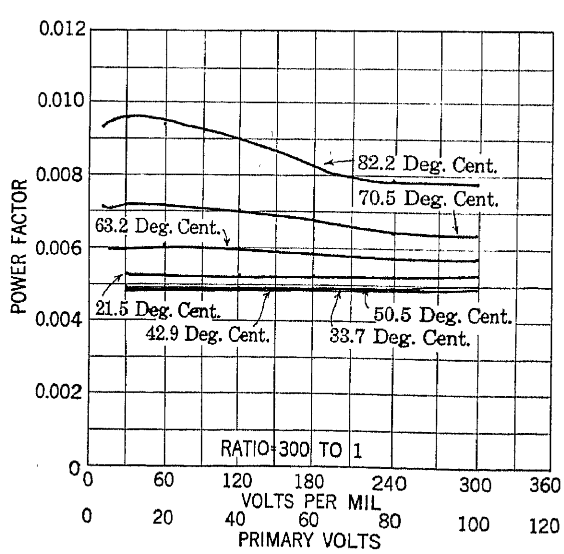

FIG. 40—POWER-FACTOR—VOLTAGE CURVES—SPECIMENS 5A, 5C IN PARALLEL

Conductor diameter 1 in. Insulation, = 0.1-in. wall
Impregnated at 1-cm. pressure

in order to provide test electrodes necessary in samples of short lengths. In our methods of test the electrodes, which correspond to the lead sheath, were applied to the cable before impregnation. It thus appeared desirable to study the question as to the influence of air lying between the outer wall of insulation and the lead sheath-ing. With this purpose in view, samples A and C of set No. 5 of our series were equipped with electrodes before impregnation in the regular manner. Sample B was impregnated before the electrodes were applied.

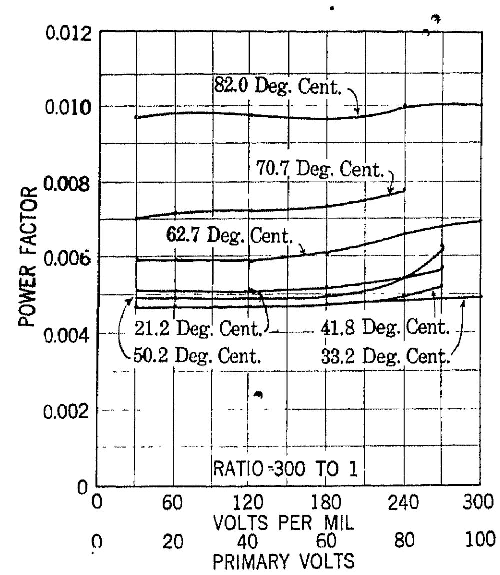

FIG. 41—POWER-FACTOR—VOLTAGE CURVES—SPECIMEN 5B—LOOSE SHEATH APPLIED AFTER IMPREGNATION TESTS UNDER COMPOUND

Conductor diameter = 1 in. Insulation = 0.1-in. wall
Impregnated at 1-cm. pressure

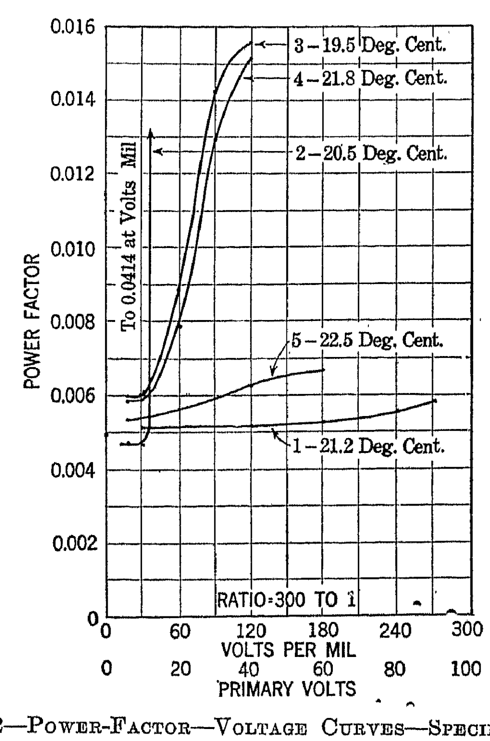

FIG. 42—POWER-FACTOR—VOLTAGE CURVES—SPECIMEN 5B—INFLUENCE OF TIGHTNESS OF SHEATH

The electrodes were applied first loosely and afterwards tightly.

Fig. 40 shows the observations on 5-A and 5-C and Fig. 41 shows the observations on specimens 5-B; the observations being taken under compound. It will be noted that there is a pronounced influence of the loose

electrode in causing the power-factor curves to turn upward at all temperatures. By far the most striking indication of the influence of a loose application of the sheath after impregnation is shown by the observations on 5-B taken in the air, that is, not under compound, and with varying degrees of tightness of the sheath. These are shown in Fig. 42. These curves were taken with conditions approximately, as closely as we were able, the conditions that are met in manufacture. There is no question of the great im-

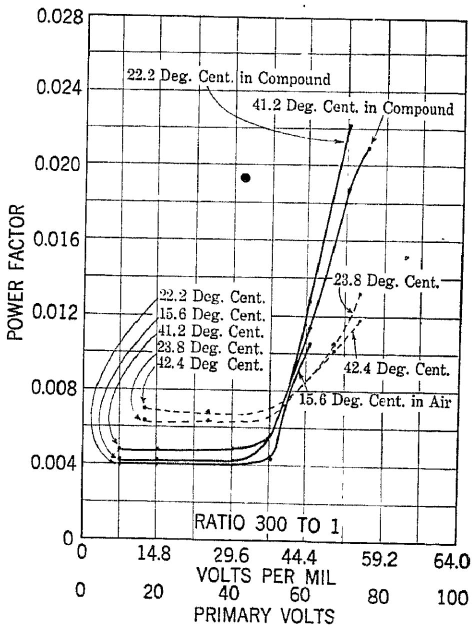

FIG. 43—POWER-FACTOR—VOLTAGE CURVES—COMMERCIAL CABLE "C"—22-KV., SINGLE-CONDUCTOR, 500,000-CIR. MILS. 13/32-IN. INSULATION

Measurements by E. T. L. on 13-ft. lengths
Measurements by J. H. U. on three-20-in. lengths

portance of the layer of air between the lead sheath and the wall of insulation. It should be noted that with test electrodes applied as tightly as possible after impregnation there is still present the rising tendency of the power-factor—voltage curves.

Figs. 43 and 44 show further studies of the influence of the tightness of the sheath. Fig. 43 shows a comparison between our tests on short lengths of cable C, and tests made on other samples taken from the same lot of cable by the Electrical Testing Laboratories. Fig. 44 shows tests on cable D under various conditions in which effort was made to alter the closeness of the fit between sheath and insulation. Strapping down tightly the ends of the lead sheathing, removing same and applying a tight electrode by our methods, and bending the sample in various ways changes the performance very little. The fact that these curves were all taken under compound, which from our experience, always tends to keep the curves at their nearest approach to horizontal form, again indicates that air between the sheathing and the insulation plays an important part in causing the break of the power-factor curve away from the horizontal.

The several measurements, described above, all seem to indicate clearly the influence on the power-factor curve of an air layer between lead and paper. This does not necessarily mean that deeper lying films of air may not play their part. On the contrary, it indicates that if such layers are present they, too, must necessarily cause a rising break in the power-factor curve.

Thanks are due to Dr. William B. Kouwenhoven for much helpful cooperation throughout the course of the work which was done in the School of Engineering, The Johns Hopkins University, at the request of the Subcommittee on Impregnated Paper Insulated Cable Research, of the National Electric Light Association, D. W. Roper, Chairman. Further studies under the same auspices are continuing.

SUMMARY AND CONCLUSIONS

1. In the drying of cable paper at atmospheric pressure the great proportion of absorbed moisture is

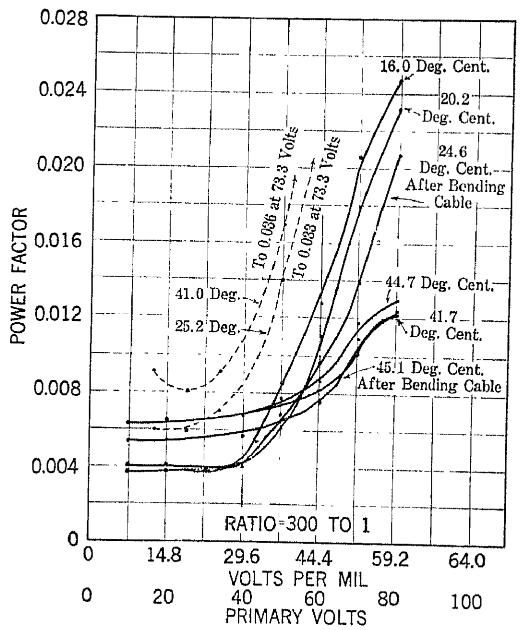

FIG. 44—POWER-FACTOR—VOLTAGE CURVES—COMMERCIAL CABLE "D", 22-KV., SINGLE-CONDUCTOR—500,000 CIR. MILS. 13/32-IN. INSULATION

Measurements by E. T. L. on 15 ft. length
Measurements by J. H. U. on 3-20 in. lengths

given off between 75 deg. and 80 deg. cent. At lower temperatures, the electrical conductivity under the continued application of voltage increases with time in accordance with the Evershed effect. At higher temperatures the paper takes on the characteristics of a highly absorbent dielectric.

2. In drying by elevation of temperature the final steady state of the paper depends on the temperature,

the time, and on the relative humidity of the atmosphere. Similar examples carried through the same drying process but at different times may have widely different residual moisture and electrical properties. A drying period of 72 hr. at 105 deg. cent. in a dry atmosphere renders cable paper an excellent insulator, although it still contains moisture and shows high dielectric absorption.

3. The evacuation process following that of temperature drying is principally important as removing still further residual moisture. It is not, however, so important in this particular as the initial drying period. Differences in the humidity of the initial drying period show themselves through subsequent evacuation periods at 1, 2, and 3 cm. Hg. pressures, and above.

4. After impregnation, the conductivity and absorption are greatly increased at the higher temperatures, but near atmospheric temperature the values are approximately the same as for the dry unimpregnated paper. The differences are apparently due to the conductivity of the impregnating compound.

5. Using a drying and evacuating and impregnating period of four days we have found for all pressures of impregnation up to 10 cm. Hg., and for temperatures up to 50 deg. cent. power-factor–voltage curves which are perfectly flat over the range 20 to 300 volts per mil, at values in the neighborhood of 0.005. At higher temperatures, the curves are higher and show maxima near 45 volts per mil, the power factor *decreasing* steadily thereafter with increasing stress.

6. Up to 10 cm. Hg., impregnating pressure differences in the original state of the samples as regards moisture reflect themselves in small changes in the values of final power factor without material influence on the shape of the curves. High moisture content increases the power factor.

7. Up to 10 cm. Hg., the pressure of impregnation causes no tendency of the power-factor curve to break and rise, usually attributed to gaseous ionization. Above 10 cm. pressure rising power-factor curves appear, reaching the typical ionization shape at 25 cm. pressure.

8. Typical gaseous ionization curves have been obtained and controlled by variations in the tightness of the lead sheath or test electrodes. It appears that the rising power-factor curves found in cables are in all probability due either to loose fitting sheaths or to imperfect impregnation, causing extended layers of air rather than to original entrained air as dependent on the evacuation pressure.

9. Power factor and dielectric absorption follow similar curves and the latter is suggested as a promising method for the predetermination of the properties of cable insulation.

The Electric Arc and its Function in the New Welding Processes

BY P. ALEXANDER[1]

Member, A. I. E. E.

Synopsis.—*The subject of this paper is a phenomenon of great interest and very great complexity. The electric arc is a tool of extreme power and flexibility. The electric arc can be used to melt the most refractory substances, cut the armor plates of battleships or weld together the ends of wires no thicker than a human hair. It is a wonderful tool that makes or breaks almost anything. It may unite the most indifferent elements such as nitrogen and oxygen, or break the molecule into its constituent atoms.*

In this paper we shall discuss only one type of application of the electric arc; namely, the application of the arc to the welding of metals, but even in these limits the field is very wide.

The electric arc was discovered by H. Davy who in 1810 was experimenting with the sparking between two horizontally disposed carbon pencils. The density of the current was such that on short circuit the tips of the carbon pencils were heated to incandescence. When the electrodes were separated the electric current continued to flow across the air-gap between the carbon pencils. The air-gap was bridged by some sort of an extremely bright band which under action of the accending currents of hot air was bent upwards and formed a bow or an "arc." This is the origin of the term, the "electric arc."

For many years the electric arc was used only as a source of light. It was only years later that the electric arc was applied for the purpose of melting and welding metals together. In 1881 de Meritens for the first time used a small carbon arc for melting and welding the lead terminals of storage batteries. The more extensive application of the carbon arc was done by Bernardos.

This process was modified by Dr. Zerener of Berlin, Germany, who shortly prior to 1890 invented a process of welding with a flaming arc. In this process two carbon electrodes are disposed to form a "V". The arc is drawn between the two electrodes and caused to impinge upon the metal to be welded by being forced down by a powerful electromagnet. This arrangement caused the arc to act in a similar manner to the flame of an oxyacetylene flame. The energy developed in this arc is only partly transmitted into the weld and the efficiency of the method is very low.

The third type arc welding known now as a metallic arc process was discovered about 1890 by H. Slawianoff.

This engineer conceived the idea of producing steel ingots by an electrical casting process. Metal was deposited from a steel rod into a mold, an electric arc being maintained between the rod and the metal of the mold. Means were provided whereby the metal rod could be fed forward as it was consumed and a solenoid arrangement was provided for maintaining the arc length substantially constant. The ingots obtained under such conditions proved to be sound and free from shrinkage pipes. However, the cost of electrical energy in Russia in those days was very high and the process was commercially uneconomical.

The information obtained by Slawianoff in this work led to the application by him of the metallic arc to the uniting together of metal plates, the repairing of cracked and broken machines, etc.

Thanks to the work of Slawianoff we now possess a method of welding with metallic electrodes which at present is by far the most used of all arc welding processes.

Electric Arc

The metallic welding arc is a phenomenon of great complexity. It is a combination of three distinct features; namely, conduction of the electric current, melting of the plate, and deposition of the metal from the rapidly melting electrode. The first feature in itself is a complicated phenomenon, which can be understood better if we consider it after reviewing the accepted ideas on electric conduction in solid conductors and in vacuum tubes.

The electric current flowing through the solid conductor has been demonstrated by the experiments of Talman and Stewart to consist wholly of electrons. The positive ions form a rigid frame-work and participate only in the vibratory movements due to the thermal agitation. The whole space is occupied by the spheres of action of the atomic forces. And between atoms there is a continual exchange of the electrons. At any instant there is a number of electrons in transition from one atom to another. These dartings from one atomic system into another are especially numerous in good conductors, and the electrons which during that short flight do not belong to any atomic system are termed free electrons. In the absence of an electromotive force, these movements are equally distributed in all possible directions, and the resultant of those elementary currents is zero. When a difference of potential is, however, impressed on the conductor, these disorderly migrations acquire a certain orientation so that more electrons will be moving in the direction of the positive pole.

An idea of the number of moving electrons may be obtained if we will try to visualize the number 1.6×10^{19} which represents the number of electronic dartings during one second through the cross-section of the conductor when it is carrying a current of one ampere. However great this number may seem, it is not the total number of electronic dartings but only a difference between those directed towards the positive and negative poles.

The conduction through the space not occupied by the solid conductor is electronic only in case of extremely high vacuum. In this case the electrons shoot from the cathode in straight lines across the empty space between the comparatively few molecules present which in extremely high vacuum can be in the order of a hundred million per cubic centimeter. Since the molecules themselves are mostly an empty space with a few specks representing the central nuclei and outer electrons, the high speed electrons can also shoot through them without being stopped or deviated.

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Presented at a meeting of the Lynn Section, A. I. E. E., Lynn, Mass., May 18, 1927.

When the cathode is cold the voltages necessary to produce such electronic currents would be of the order of millions of volts and the obtained currents expressed in milliamperes. In other words, for most purposes a space not occupied by either solid or gas of sufficient density is an insulator. There will not be any change in conductivity if a gas in a perfectly neutral state be introduced between the electrodes. The distances between the gaseous molecules, even if their number is increased to several billion of billions per cubic centimeter, are relatively so great that there cannot be any exchange of electrons as in solid conductors between the atoms and the space remains non-conducting. This, however, will cease to be so if the molecules acquire electrical charges.

Under usual conditions gases are subjected to various ionizing radiations such as the radioactivity of the earth, ultra violet rays, and the electrons emission from the hot bodies and flames. In atmospheric air these factors determine a generation of two to three ions per second per cubic centimeter. However small the degree of ionization may be, the gas will always contain a few ions and free electrons. If an electron moving under the influence of applied difference of potentials with sufficient velocity encounters or passes very near one of the outer orbital electrons of an atom, the repulsive forces between them may be such as to detach the orbital electron from the atomic system, which then remains with a unit positive charge. The removed electron may either repeat the same process with the next molecule or attach itself to it, thereby communicating a negative charge. This removal or attachment of one extra electron to the neutral molecules is called ionization.

Electrons so produced and ionized atoms or molecules will also start moving in the direction of the electric force and if the potential gradient is sufficient, will acquire such velocity that their impact on neutral molecules will ionize these. This process of cumulative ionization in a very short time will produce a sufficient number of carriers to transmit from one electrode to another a considerable current. Under certain special conditions, the highly ionized gas column may acquire an electric conductivity comparable with that of a good solid conductor. It might seem strange that a gaseous column can be almost as good a conductor as a copper rod, yet if we remember that the conduction depends only on the number of suitable carriers and on the velocity with which they can move this apparent paradox disappears. Now to pass from conduction through ionized gas to arc conduction, we shall consider the effect of the temperature of the cathode. When the cathode is brought up by some means to a high temperature the electrons will be ejected from its surface into the gas in great numbers. These free electrons can be considered as ions and the gas containing such electrons as an ionized gas. The voltage necessary to move these free electrons towards the anode can be comparatively low. If the gas is at a very low pressure, the electrons will move in straight lines between the molecules. Only a very few of these electrons will be stopped or deflected by collision with molecules. In this case the current will be purely electronic. However, when the molecules are present in larger numbers the electrons (if moving with sufficient velocity) will ionize the gaseous molecules and the current will be carried by ionized molecules as well as by the electrons.

The method of producing the intense initial ionization in the case of an electric arc is by taking advantage of the above described property of certain materials to emit electrons at high temperatures. To draw the arc between the two electrodes, they are brought in contact and a current of sufficient magnitude is passed across the contact. The resistance of the contact, especially just before the moment of separation of the electrodes, is high enough to cause rapid heating of the tips of the electrodes to incandescence, with the result that numerous electrons are projected into the surrounding gas, so that at the moment of separation of the electrodes, the gas contains large numbers of free electrons which under the action of the established electrostatic field will move and impinge on the gaseous molecules.

Since the separation of the electrodes is done gradually, even with comparatively low voltages the potential gradient during the first moment will be sufficient to give the necessary acceleration to the free electrons which at the end of their free path will possess energy to ionize the gaseous molecules. The ionized molecules and electrons will move and impinge on the next neutral molecules but unless the potential gradient is sufficiently high, they will not acquire at the end of their free path a sufficient velocity and consequently will be unable to ionize the next set of molecules; therefore, the ionization will not continue. Since the distance between the electrodes continued to increase and the potential gradient to decrease, the current, after reaching certain magnitude, will fall to a lower value and finally stop altogether. But if the potential gradient during the separation of the electrodes be sufficient, the number of carriers will increase very rapidly until an appreciable current will flow between the electrodes which will produce rapid heating of gas. At higher temperatures the ionization occurs much more readily, so that as soon as the appreciable current flows, the ionization is more pronounced which again causes the current to increase. As soon as the cathode spot on the electrode is brought to a high temperature, a large volume of metallic vapor is sent into the stream which is easily ionized and will conduct practically the whole current. This is the arc conduction.

Since the drawing of the arc is done at a low temperature and the maintaining of the arc at high temperatures, the voltages necessary to strike the arc are always much higher than those used to maintain the arc.

This feature is taken advantage of in the design of a number of commercial welding generators which produce a high voltage only on open circuit. As soon as the arc is drawn, the voltage across the brushes automatically falls to a value only slightly higher than that of the voltage across the arc.

Since high temperature is essential to maintain easy ionization, any factor tending to cool off the electrodes or the arc stream will influence greatly the stability of the arc. If the temperature of the arc falls, the ionization of the materials in the arc stream does not take place as readily, so that the agent producing ionization must be more active. In other words, the speed with which the electrons and ions impinge on the neutral molecules must be higher which necessitates a high potential gradient; that is, higher arc voltage. One of the most powerful methods of cooling the arc core is by surrounding it with hydrogen, which at high temperature dissociates into the atomic state and absorbs large amounts of energy.

Atomic Hydrogen Process

This phenomenon of dissociation of molecular hydrogen at high temperatures into the atomic state was discovered by Dr. I. Langmuir[2] during his studies of the laws of heat losses from a heated tungsten filament in hydrogen at low pressures. Dr. Langmuir observed that above certain temperatures, the heat losses instead of being proportional to 1.9th power of the absolute temperature, are proportional to a much higher power which increases with temperature.

The following studies of this phenomena established that these abnormally high losses are due to the dissociation of molecular hydrogen into the atomic state. Step by step Dr. Langmuir discovered the temperatures of dissociation, degree of concentration of the produced atomic hydrogen, the energy absorbed by the dissociation, the chemical properties of the atomic hydrogen and the thermic effects produced by recombination of the atoms into molecules.

The atomic hydrogen possesses many remarkable properties which have been studied in the last few years by several investigators. Many chemical reactions impossible with molecular hydrogen take place when that gas is in the atomic state. The most stable oxides can be reduced into the metallic state. Substances which are usually considered as the most refractory materials can be melted by the flames of atomic hydrogen. And certain hydrogen compounds which formerly could be produced in very small concentrations, now may be obtained in 100 per cent concentrations. There are two methods of producing atomic hydrogen.

One discovered by Dr. Langmuir is by increasing the speed of the thermal agitation of hydrogen molecules until the forces between the two atoms composing the molecule are not sufficient to hold them together. They spring apart and by doing so absorb large amounts of energy from the source producing that thermal agitation. In this method all molecules subjected to the high temperature are being acted upon simultaneously. This is (if we can use such a term here) a "mass production."

The other way of disrupting the hydrogen molecule is by hitting it with a heavy atom, moving with high velocity. In this method the hydrogen molecules are dissociated one by one and only when shot with a swiftly moving atom. Using again a shop term, we can call it "piece work." However, Dr. Langmuir developed the first method which permits the production of atomic hydrogen in high concentration, which permits the use of atomic hydrogen not only as a special chemical regent but also as one of the most remarkable agents for transmission of thermal energy. To accomplish this, it was necessary to produce the atomic hydrogen not inside of a vacuum container, but in the open air. The method adopted by Dr. Langmuir consists in blowing a stream of molecular hydrogen through an electric arc maintained between two tungsten electrodes.

The temperature of the arc core is sufficient to produce complete dissociation of the whole mass of the gaseous layer in contact with it. The produced atomic hydrogen diffuses rapidly away from the arc core and recombines in the cooler regions into the molecular state, forming an extremely hot flame of a single gas which burns without oxygen. The evolved heat, of course, is the energy previously absorbed from the arc. It was found that the heat of formation of molecular hydrogen is equal to 98,000 calories. In other words, when the atomic hydrogen recombines to produce one cubic foot of molecular hydrogen (measured at N. T. P.), the amount of heat produced is 455 B. t. u This quantity is greater than that obtained by the combustion of one cubic foot of molecular hydrogen in oxygen. In the last case the amount of evolved heat will be only 316 B. t. u.

The greatest advantage of the atomic hydrogen resides not in the amount of energy transmitted but in the high potential at which that energy is delivered. In other words, the remarkable property of the atomic hydrogen is the temperature o its flame. Dr. Langmuir's calculations show that this temperature is at least 3717 deg. cent. One of the experimental confirmations of these conclusions is the fact that tungsten, the metal with the highest known melting point, can be melted in the atomic hydrogen flame but not in any other flame.

The importance of the temperature of the flame can be illustrated by the comparison of two combustible gases; one of which is acetylene and another is propane. The amount of energy produced by combustion of one cubic foot of acetylene is 1456 B. t. u. The corresponding value for propane is 2465 B. t. u.

2. Flames of Atomic Hydrogen, *General Electric Review*, March, 1926.

In spite of much lower heat capacity of acetylene, the temperature of its flame (about 3000 deg. cent.) is higher than that of propane (about 2100 deg. cent.) and the result of it is that the welding with that gas is much faster than with the latter.

One of the practical applications of the atomic hydrogen flame is for welding of metals. In this field it has received lately numerous applications on account of its two properties especially valuable for welding work; namely, the extremely high temperature of the flame and the reducing properties of the gas forming that flame.

As a welding tool the atomic hydrogen torch must be compared with the oxyacetylene torch. It has similar characteristics in that the most of the energy is produced in a comparatively small inner cone or fan where extremely high temperature is attained. This inner hot zone is surrounded by the flame of reducing gas with temperatures gradually falling to that of the outer mantle of the flame where the recombined molecular hydrogen is burning in contact with the air. The temperature of that part of the flame is something like 1000 deg. cent.

This gradual change of emperatures gives an extreme flexibility to the atomic hydrogen torch. It insures a perfect control of speed of welding and of the temperature of the molten metal in the weld. This last factor is of a paramount importance for welding in hydrogen atmosphere. This gas is only slightly soluble in molten iron ust above the melting point. But with a rise of temperature its solubility increases very rapidly. When the molten iron is overheated, it will absorb at least 15 times its own volume of gas (measured at N. T. P.). During the solidification most of that gas will be precipitated out and unless special precautions are taken, will form numerous blow holes.

However, if the welder follows the right technic by forming only a shallow pool of molten metal which insures a low temperature of the molten iron, hydrogen will be prevented from going into solution and the resulting weld will be perfectly free from gas pockets.

The atomic hydrogen torch embodies in itself all the necessary conditions not only to transmit from the arc into the plate any desired amount of energy, but also to do it at a very high speed. The high speed of recombination of the atomic hydrogen into the molecular state is determined by the steep gradient of temperatures and also by the catalytic action of the metal in the weld.

This recombination of the atomic hydrogen at the surface of the liquid metal in the weld to a certain extent replaces he oxidation reaction always present when the welding is done in air. This reaction supplies the necessary auxiliary heat to keep the surface of the solidifying metal in the molten state long enough to permit the absorbed gases to escape freely.

The a-c. arcs used in the atomic hydrogen process are usually two or three cm. in length bent in a shape of a fan between two tungsten electrodes placed to form a "V". The voltage drops at the surface of the electrodes, which correspond to anode and cathode drops in d-c. arcs, are equal to about 18 volts each. With the usual arcs of about 100 volts, the 36-volt drop at the surface of the electrodes, therefore, represents one-third of the total arc voltage, so that two-thirds of the energy absorbed in the dissociation of hydrogen into atomic state comes from the long arc core. The usual arc voltage is about 100 volts and the open circuit voltage of the welding circuit is seldom less than three or four times that value. The energy absorbed by the weld, of course, is that which comes from the arc; the atomic hydrogen plays the role only of an exceptionally efficient transmitter.

The energy evolved by burning the molecular hydrogen in contact with the air, serves only to raise slightly the temperature of the plate outside the weld but does not affect appreciably the weld itself. Most of that energy is radiated into surrounding space.

The Shielded Arc Process

While the work on atomic hydrogen was proceeding in the Schenectady Laboratory, the writer was engaged in the Lynn Laboratory on the development of an improved method of the arc welding with metallic and carbon electrodes.

Since the accepted explanation of brittleness in arc welds was the presence in the weld of oxides and nitrides of iron, the first experiments were conducted on welding in gases other than those composing the atmospheric air. The first experiments were conducted on welding in carbon dioxide, superheated steam, and illuminating gas. Then, without any knowledge of Dr. Langmuir's experiments with atomic hydrogen, the writer came to the conclusion that it is hydrogen which must give the desired results. The experiments immediately confirmed this view. The welds produced in that gas proved to be perfectly ductile and to possess a high tensile strength. Furthermore, it was found that the apparent resistance of the welding arc in hydrogen is more than twice that of the same arc in air. Because of the desirability of rapid deposition of the metal, the welding arc must have a definite short length. The increase of the apparent resistance of the arc without increase in length is most welcome as it makes the arc almost twice as efficient as a device for the transformation of the electrical energy into the thermal form.

The anode and cathode voltage drops of an iron welding arc of 100 amperes maintained in hydrogen atmosphere were found to be each equal to 16 volts. The voltage drop across the arc stream for an arc of 1/8 inch does not exceed 5 volts, so that the total voltage across the arc of 1/8 inch in length is 37 volts. The usual arc voltage of the welding arcs of the same length and current intensity maintained in air is about 18 volts.

This abnormal apparent resistance of the arc in

hydrogen, the writer at that time attributed to an xe-ceptionally high coefficient of heat conductivity of that gas. Indeed the heat conductivity of air is 0.5×10^{-5} and that of hydrogen is 3.17×10^{-5} calories per cm. per sec. per deg. cent. In other words, it was thought that the high voltage of the arc is due to a mere cooling of the arc by hydrogen in its molecular form.

At a later date, to check up this assumption, the writer repeated the same experiments with the arcs in helium. This gas has also an exceptionally high coefficient of heat conductivity which is even slightly higher than that of hydrogen; namely, 3.39×10^{-5}. The experiments, however, showed that the arc voltage in that gas is lower even than in air. Since the coefficients of diffusion of hydrogen and helium are about the same and the temperature of the arc core in both cases probably does not differ materially, the only explanation of difference in the arc voltages was that the hydrogen, being a diatomic gas, was dissociated into the atomic state while the helium, being a monatomic gas, remained unchanged by the extreme temperature of the arc.

These experiments have an interest only as illustration of various ways of investigation. The quantative determination of the amount of atomic hydrogen produced cannot be based on such experiments. They only demonstrate the fact of the dissociation of hydrogen into the atomic state and that it affects very markedly the anode and cathode fall.

These two quantities are determined by the concentration of the ions of one sign at the surface of the electrodes. If the production of the ions of the other sign in the first gaseous layers next to the electrode is slowed down, the electrostatic charges of the incoming ions will determine a very steep potential gradient. The dissociation of hydrogen into the atomic state cools off the surface of the anode and cathode and, therefore, reduces there, the speed of ionization and emission of thermions. The role of atomic hydrogen in the shielded arc process can be compared with the most effective means of cooling the electrodes.

Of course, the atomic hydrogen produced undoubtedly affects also the quality of the weld, making it more free from oxides. This last action, however, is not as important as that which increased the efficiency of the arc, since in the shielded arc process, the weld is fully protected by a large volume of the molecular hydrogen which at the high temperature of the arc is also one of the most energetic reducing agents.

The Deposition of Metal

The transfer of the metal from the electrode to the plate can be either purely ionic or mechanical. In the first case the metal is rapidly vaporized from the electrode, enters the arc and after being ionized is moved across the arc to the surface of the positive crater where it regains its state of neutral atoms and condenses as a vapor on the surface of the crater. The speed of motion of gaseous ions is very high so that large quantities of metal can be transferred from the electrode to the weld in a very short time. The hypothesis of transfer of the metal in the state of vapor has been advanced by Professor Slocum.[3] This type of metal transfer is observed only with long arcs.

The writer's experiments indicated that the temperature of the anode is the determining factor in the ionic transfer of the metal in the welding arc. If an arc of 125 amperes and 60 volts be maintained in hydrogen between a cold plate and ⅛-in. Armco pure iron electrode, the transfer of metal will be mostly mechanical. The tip of the electrode will be liquified and the large drops of metal will be periodically falling down on the plate. The vapor stream from the negative electrode will enter the arc, but there will not be appreciable condensation of that vapor on the plate If, however, the positive crater be allowed to establish itself on the plate and the temperature of the molten metal in the crater rises above a certain limit, then the arc will become very stable and practically the total amount of metal will pass through the arc in a state of ionized vapor. The speed of "vapor deposition" of metal is about the same as that which would be with the short arcs of the same current density when practically the total amount of metal is passing through the arc in the liquid state. However, in usual practise, the arc length is so short that the intense radiations from the positive crater affect not only the surface of the negative crater but also the whole tip of the electrode to a considerable length. This results in rapid melting of the tip of the electrode which is in more or less plastic state to a distance of three or four millimeters from the negative crater. This condition determines an entirely different mode of transfer of metal across the arc. The wire used as electrodes always contains a large amount of occluded gases. The actual volume of occluded gases depends on the method of manufacturing of the wire and in certain instances may reach many times the volume of the metal.

The amount of gas which the metal can hold in the occluded state depends on the temperature. At the temperature of red heat, most of the gases are expelled from the metal. Since the tip of the electrode is in molten state, it is mechanically the weakest point and the gases escape in that direction which results in periodical rupture of the liquid surface of the tip of the electrode and projection of it into the direction of the positive crater. If the arc is very short, this ruptured part of the tip of the electrode short-circuits the arc. In other words, it bridges the tip of the electrode with the positive crater. As soon as the globule touches the liquid surface, another set of forces comes into play; namely, the surface tension of the molten metal. Now the globule is pulled towards the liquid by the surface

3. The Welding Arc. *Welding Engineer*, January, 1921.

tension and so breaks the contact with the electrode. If the time of transfer was short, the temperature of the ionized gases was not affected appreciably so that the arc can be readily restarted. The experimental proof of this mechanism of transfer of molten metal across the welding arc was furnished by many investigators amongst whom we must name Professor Hudson[4] who advocates the theory of liquid transfer of metal determined by the expulsion of the gases, and Mr. O. H. Eschholz[5] who demonstrated that even without the explosive action of gases, the metal can be transferred through the action of the forces of the surface tension. However, the writer is of the opinion that both types of forces are responsible for the transfer of the metal in the short welding arc.

Physics and Chemistry of the Crater

In the case of arc welding with a metallic electrode, the positive crater is established on the plate itself. This is the most efficient method of transmitting the energy of the arc into the plate. In this case not only the metal is subjected to the radiations from the negative crater and the arc core, but it is also the subject of the most terrible bombardment by the electrons and ions rapidly moving towards the anode. The velocity of gaseous ions in the arc core is not definitely known but it may be expected to be very high. Furthermore, the condensation of the gaseous ions on the liquid surface of the crater is accompanied by the evolution of the latent heat of evaporation of electrons and gaseous atoms. This last factor explains the difference in the calorific effects at the anode and cathode of the arc in spite of the fact that the anode and cathode potential drops, as in the case of the iron arc in hydrogen, are the same. The surface of the metal is heated so rapidly that the heat has no time to be conducted away through the thickness of the metal. Therefore, the metal around the foot of the arc core is liquefied and forms a shallow molten pool. The metal in this molten pool is a subject of several actions. First, the rapidly falling metallic globules splash the molten metal so that the surface of the crater is continually swept by the waves running from the center of the crater to the periphery. Secondly, the molten metal, being free to move, is repulsed from the foot of the arc by the electromagnetic interaction of the currents carried by those parts of the arc and moves towards the edges of the molten pool, forming a sort of a shallow cup or a crater.

The absorption and evolution of gases in different parts of the crater is a factor of paramount importance. The accurate tests conducted by Dr. Baraduc-Muller,[6] who was experimenting with the masses of molten steel weighing 11,000 pounds, demonstrated that molten steel may hold in solution very large amounts of gases. For instance, the volumes of hydrogen, carbon monoxide and nitrogen occluded in one cubic foot of molten Bessemer steel are respectively equal to thirteen, eight and five cubic feet (measured at N. T. P.).

The writer's experiments with hydrogen, helium, argon, carbon monoxide, and nitrogen occluded in the molten part of the crater gave about the same figures and indicated that these gases are precipitated out from the molten steel when it is still fluid. The observation of the large craters of the powerful arcs burning in different gases reveals that all these gases are absorbed in the hot part of the crater and evolved in a form of a stream bubbles coming to the surface of the molten metal in cooler parts of the crater.

This continual process of absorption and evolution of gases is equivalent to an energetic washing of the molten metal with hot gas. The occluded gases may react with the metal and form nitrides, oxides, hydrides or may simply be held in solution and be partly precipitated out during the solidification. At any rate the large amounts of absorbed and later evolved gases have a very great bearing on the soundness of the deposited metal and the number of blow holes which it may contain.

When the arc is maintained in air, the fundamental chemical reaction in the crater of the arc is oxidation. Oxygen of the air coming in contact with the molten metal reacts almost instantaneously and forms $Fe\,O$ which is gradually dissolved in the mass of the metal. The excess of that oxide floats on the surface in a form of a slag and being further oxidized during the freezing of the metal to $Fe_3\,O_4$. The oxidation or burning of the surface layer of the molten metal in the arc crater has a determining influence on the number of gas inclusions in the weld metal. As has been demonstrated by the writer's experiments on welding arcs in argon-oxygen mixtures,[7] the amount of heat produced by the oxidation reaction is sufficient to maintain the surface of the freezing metal near the edge of the crater in molten state long enough to allow all the gases to escape freely and leave the weld metal free from blow holes.

When the deposition of the metal is done in reducing or neutral atmosphere, this reaction is suppressed and unless special precautions are taken, the weld metal will contain numerous blow holes.

It may be pointed out here that in the atomic hydrogen process, the recombination of the atomic hydrogen into the molecular form at the surface of the weld metal provides a source of large amount of energy. In this way the atomic hydrogen process not only suppresses the deleterious action of oxidation but also provides means to replace the important and desirable influence of that reaction by a new reaction which takes

4. A Theory of Metallic Arc Welding, *Journal of Am. Welding Society*, October, 1919.

5. Metal Deposition in Arc Welding, *Electrical World*, June, 1920.

6. The Gases Occluded in Liquid Steel, *Iron and Steel Institute Carnegie Scholarship*, Memoir, 1909.

7. Oxidation of the Arc Crater, *Journal of Am. Welding Society*, December, 1926.

place of the old one. In the shielded arc process, other means are used to assure the prompt expulsion of the occluded gases.

Welding in Mixed Gases

The development of the shielded arc process extended also to the making of welds in mixtures of hydrogen and carbon monoxide according to the ideas of Prof. E. Thomson.

The tests demonstrated that the metal deposited in that atmosphere possessed about the same ductility as those produced in pure hydrogen. Furthermore, it was found that the arc in water gas is much more stable than in hydrogen and does not necessitate the open circuit voltage even for welding with comparatively low currents, higher than used for standard work of welding in air.

Other tests were made with various gaseous mixtures. In conjunction with Professor Thomson the author found that not only various mixtures of hydrogen and carbon monoxide could be used for welding work, but that certain organic liquids such as methanol and denatured ethyl alcohol when vaporized will serve the same purpose as the pure hydrogen.

Working in conjunction with Dr. Langmuir, the author also carried out a series of tests which demonstrated that for certain purposes nitrogen mixed with certain amounts of hydrogen gives welds of superior quality. It should be mentioned here also that the mixture of hydrogen with argon was suggested to the writer by Mr. P. K. Devers.

The work conducted on welding in various gases resulted in the development of practical means of producing these gases easily and at a low cost from various organic and inorganic compounds such as alcohols, ammonia, propane, etc. Since these compounds are liquids or liquefied gases, the question of storage and transportation has also been solved. This can be made clear if we consider that one gallon of methanol will give on vaporization and dissociation in the arc over 240 cubic ft. of gas. The development of welding in alcohol vapors should be especially emphasized as one of the most practical solutions found in this laboratory of the problem of storage and cost of the most suitable gas for welding by the shielded arc process which is water gas.

When instead of pure hydrogen, the shielding gaseous atmosphere is provided by the gaseous mixture of carbon dioxide with propane or the vapors of alcohol, the function of the arc is not only to liberate sufficient amount of energy to melt the metal but also by dissociating the gaseous raw materials, produces a suitable mixture of hydrogen with carbon monoxide. The electric arc here becomes not merely a source of heat but also a chemical laboratory.

If we try to visualize all that is happening in the small space occupied by the arc, all the different chemical reactions, transformation of electrical energy into thermal form, absorption and evolution of gases and the deposition of metal, one begins to wonder how it is possible for the welder to take care of all these complicated factors. The answer is that they take care of themselves. If the conditions are regulated rightly, all these processes are entirely automatic and the man has to watch only the needle of the meter.

After going through this description of the atomic hydrogen and the shielded arc processes, one may ask, "What is the purpose of this development? What is all this for? Is it easier to use a combination of the electric arc with the gas instead of using each of these factors singly?"

The answer to the last question is "no." Of course, the combination of several factors necessitates better technique and more accurate adjustment of all the conditions. But what is complicated today will be a simple thing tomorrow.

It is simpler to make a lamp with the tungsten filament in the vacuum than a combination of the same filament and the gas. But who wants now the older and simpler type of the incandescent lamp? The present arc welding processes are all right and give excellent results in every field of their applications. But so did the rivet thirty years ago.

There was a time when no one dreamed of using anything but pure wrought iron. Then there came an age of iron-carbon alloys; that is, of steel. And now we are entering the era of alloy steels. Most of those steels contain such easily oxidizable elements as chromium. And unless the weld is protected by a reducing atmosphere, the results on welding such materials are not satisfactory. It is in this field that the new processes probably will find their best applications.

The electric arc and the gas flame will, in the future, replace rivet cutting tools and the foundry mold. Amongst innumerable fields of applications, there will be demand for every kind of welding and cutting processes. The described processes will not replace any of the existing processes but simply assume their place of usefulness amongst the older brothers and do the job which cannot be done without their help.

Computation of the Unbalance Factor
of a Three-Phase Triangle When Lengths of Three Sides are Given

BY A. E. KENNELLY

IN an important paper read before the June 1918 Convention of the A. I. E. E., it was shown by Mr. C. L. Fortescue that any dissymmetrical system of three-phase voltages or currents could be resolved, by vector methods, into a pair of symmetrical systems, one forward and the other backward. The numerical ratio of the latter to the former is called the unbalance factor of the system. Although several vector methods were developed in the paper and its discussion, for evaluating the forward and backward components when the dissymmetrical triangle is given, so far as is known to the writer, no scalar and purely numerical method of developing them has been published. As it is useful sometimes to compute the two components without recourse to vector methods or to the drawing board, a numerical method is here offered.

Let $A\,B\,C$, Fig. 1, be the dissymmetrical three-phase triangle, say of voltages $A\,B = 1100$, $B\,C = 1000$, and $C\,A = 900$, the system having counterclockwise rotation. One of the now well-known vector methods for deriving the forward and backward components is shown. With center A and radius $A\,C$, arcs of 120 deg. and 240 deg. are drawn counterclockwise to the points d_1 and e_1, respectively. Again, with center B and radius $B\,C$, arcs of 120 deg. and 240 deg. are drawn clockwise to the points D and E respectively. Lines $d_1\,D$, and $e_1\,E$, are then drawn as shown. Each of these lines is trisected, as at $d_1\,d_2$ and $e_1\,e_2$. Equilateral triangles $d_1\,d_2\,d_3$ and $e_1\,e_2\,e_3$ are then constructed on these segments. These are known to be the equivalent symmetrical component systems. The equilateral triangle $d_1\,d_2\,d_3$ is drawn with forward rotation or counterclockwise, like $A\,B\,C$, and the equilateral triangle $e_1\,e_2\,e_3$ with reverse or backward rotation.

The vector sum of $d_1\,d_2$ and $e_1\,e_2$ is then equal to the vector $A\,B$,

The vector sum of $d_2\,d_3$ and $e_2\,e_3$ is then equal to the vector $B\,C$,

The vector sum of $d_3\,d_1$ and $e_3\,e_1$ is then equal to the vector $C\,A$.

In this case, the sides of the forward or d triangle measure 996.6 volts, and the sides of the backward or e triangle measure 115.9 volts. The unbalance factor of the $A\,B\,C$ triangle or system is then $115.9/996.6 = 0.116$.

An equivalent numerical method is as follows:

Let A_m be the r. m. s. of the sides of the given triangle $A\,B\,C$, and let A_s be the side length of an equilateral triangle having the same area as the actual triangle $A\,B\,C$; then the side squares d^2 and e^2 of the forward and backward components will be respectively the half sum and the half difference of A_m^2 and A_s^2. Thus

$$d^2 = \frac{A_m^2 + A_s^2}{2} \tag{1}$$

and

$$e^2 = \frac{A_m^2 - A_s^2}{2} \tag{2}$$

The unbalance factor is then, as before, e/d.

Let a, b, and c, be the three known sides of the dissymmetrical system triangle $A\,B\,C$. Then the mean square of these sides is:

$$A_m^2 = \frac{a^2 + b^2 + c^2}{3} \tag{3}$$

Again, if the half-perimeter p of the triangle $A\,B\,C$ is

$$p = \frac{a + b + c}{2} \tag{4}$$

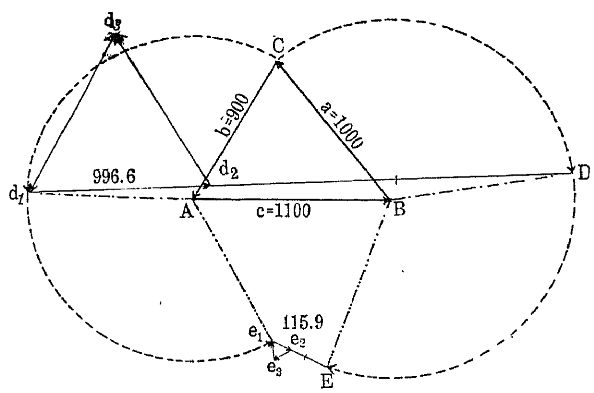

FIG. 1—DIAGRAM SHOWING ANALYSIS OF A DYSSYMMETRICAL SYSTEM $A\,B\,C$, BY ONE OF THE USUAL VECTOR METHODS INTO FORWARD AND BACKWARD COMPONENTS

it is shown in text-books of plane trigonometry that the area of the triangle $A\,B\,C$ is:

$$s = \sqrt{p\,(p - a)\,.\,(p - b)\,.\,(p - c)} \tag{5}$$

If A_s is the length of the side of an equilateral triangle $A\,B\,C$, Fig. 2, the area S of this triangle, being equal to half the product of the base A_s and the height h, we have

$$h = A_s \cos 30° = A_s \sqrt{3}/2 \tag{6}$$

so that

$$S = \frac{h\,.\,A_s}{2} = \frac{A_s^2\sqrt{3}}{4} \tag{7}$$

or

$$A_s^2 = \frac{4\,S}{\sqrt{3}} \tag{8}$$

If we take $S = s$, we have

$$A_s^2 = \frac{4\,s}{\sqrt{3}} \tag{9}$$

and A_s^2 is now the side square of an equilateral triangle equal in area to $A\,B\,C$. Then

$$d^2 = \frac{A_m^2 + A_s^2}{2} = \frac{a^2 + b^2 + c^2}{6} + \frac{2\,s}{\sqrt{3}} \tag{10}$$

and

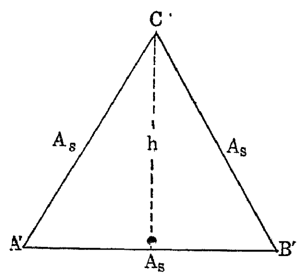

FIG. 2—EQUILATERAL TRIANGLE OF SIDE A_s

$$e^2 = \frac{A_m^2 - A_s^2}{2} = \frac{a^2 + b^2 + c^2}{6} - \frac{2\,s}{\sqrt{3}} \tag{11}$$

With the given values $a = 1100$, $b = 1000$, and $c = 900$, corresponding to the case of Fig. 1, $A_m^2 = (1100^2 + 1000^2 + 900^2)/3 = 1{,}006{,}666$, or A_m, the r. m. s. side, is 1002.66 volts. The semiperimeter p is 1500 volts, and the areas of the triangle $A\,B\,C$ is $\sqrt{1500 \times 600 \times 400 \times 500} = 424{,}264$. The squared side A_s^2 of an equilateral triangle of this area is, by (**9**), $424{,}264 \times 4/\sqrt{3} = 979{,}796.$ or $A_s = 989.846$. We then have, by (**1**),

$$d^2 = \frac{1{,}006{,}666 + 979{,}796}{2} = 993{,}231, \text{ and } d = 996.61$$

volts; while

$$e^2 = \frac{1{,}006{,}666 - 979.796}{2} = 13{,}435, \text{ and } e = 115.91$$

volts.

The unbalance factor, as before, is $115.91/996.61 = 0.1163$.

In the extreme case of a symmetrical three-phase system, represented by an equilateral triangle, $a = b = c = q$ say, and the r. m. s. side A_m is also q. Moreover the side A_s of the equilateral triangle of equal area is evidently also q. In that case, $d = \sqrt{\dfrac{q^2 + q^2}{2}} = q$, and $e = \sqrt{\dfrac{q^2 - q^2}{2}} = 0$; so that the unbalance factor vanishes.

In the opposite extreme case of a flat three-phase system, reduced to the single-phase type; so that $A\,B$, $B\,C$, and $C\,A$ are all in the same straight line, the area of the system triangle vanishes, and so does the side length A_s. Consequently, $d = \dfrac{A_m}{\sqrt{2}} = e$, and e/d, the unbalance factor, becomes unity.

A Note on the Unbalancing Factor of Three-Phase Systems

BY A. PEN-TUNG SAH

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In an article appearing in the A. I. E. E. JOURNAL for March 1927, Prof. A. E. Kennelly gave the following analytic expressions for computing the forward (positive-phase or direct sequence) and backward (negative-phase or reverse sequence) components of a dissymmetric three-phase vector triangle.

$$\text{(A)} \qquad d^2 = \frac{a^2 + b^2 + c^2}{6} + \frac{2\,s}{\sqrt{3}};$$

$$e^2 = \frac{a^2 + b^2 + c^2}{6} - \frac{2\,s}{\sqrt{3}};$$

in which a, b, and c are the lengths of the vectors forming the triangle and s its area; d and e being the magnitudes of the forward and backward components respectively. In deriving expressions (A), he started from the relations—

$$\text{(B)} \qquad d^2 = \frac{A_m^2 + A_s^2}{2};\; e^2 = \frac{A_m^2 - A_s^2}{2}$$

where A_m is the r. m. s. of the sides of the given triangle $A\,B\,C$ and A_s the side length of an equilateral triangle having the same area. Judging from the fact that Professor Kennelly did not state how (B) could be derived, this must be either self-evident or very simply derivable from his geometrical construction of the forward and backward components. However, the present writer has failed to see this and it will be shown in the following that the relations (A) can be very simply obtained from an alternative method of geometrical construction of the components.

It is well known that the following constructions for the components hold:

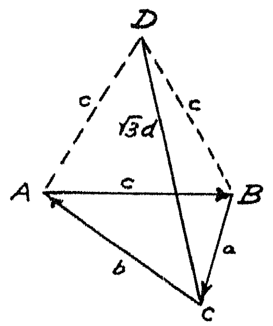

FIG. 1

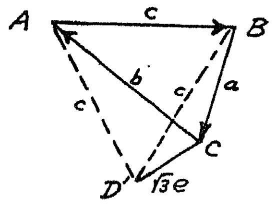

FIG. 2

Let $A\,B\,C$ be the given vector triangle. Construct an equilateral triangle $A\,B\,D$ externally on the side $A\,B$ as in Fig. 1. Then the magnitude of the forward component is given by $C\,D/\sqrt{3}$. If we construct the triangle $A\,B\,D'$ internally as in Fig. 2, we get $C\,D'/\sqrt{3}$ as the magnitude of the backward component. The lengths $C\,D$ and $C\,D'$ are readily computed. From Fig. 1 by the law of cosines, we have—

$$3\,d^2 = \overline{C\,D}^2 = b^2 + c^2 - 2\,b\,c\cos(60° + \angle\,B\,A\,C)$$

$$= b^2 + c^2 - 2\,b\,c\left[\frac{1}{2}\cos\angle\,B\,A\,C - \frac{\sqrt{3}}{2}\sin\angle\,B\,A\,C\right]$$

As $\frac{1}{2}\,b\,c\sin\angle\,B\,A\,C = \text{Area of } \Delta\,B\,A\,C = s$ and

$$2\,b\,c\cos\angle\,B\,A\,C = b^2 + c^2 - a^2,$$

$$3\,d^2 = b^2 + c^2 - \frac{1}{2}(b^2 + c^2 - a^2) + 2.\sqrt{3}\,s \text{ or}$$

$$d^2 = \frac{a^2 + b^2 + c^2}{6} + \frac{2\,s}{\sqrt{3}}$$

which is the first equation in (A).

Similarly,

$$3\,e^2 = \overline{C\,D'}^2 = b^2 + c^2 - 2\,b\,c\cos(60° - \angle\,B\,A\,C)$$

$$= b^2 + c^2 - 2\,b\,c\left[\frac{1}{2}\cos\angle\,BAC + \frac{\sqrt{3}}{2}\sin\angle\,BAC\right]$$

$$= b^2 + c^2 - \frac{1}{2}(b^2 + c^2 - a^2) - 2\sqrt{3}\,s$$

$$i.\,e., \quad e^2 = \frac{a^2 + b^2 + c^2}{6} - \frac{2\,s}{\sqrt{3}},$$

which is the second one of the relations (A).

In passing it should be noted that the constructions herein given do not give the correct phase relation of the components. To get the correct phase relation the line $C\,D$ has to be rotated through an angle 30 deg. counter clockwise and $C\,D'$ through 30 deg. clockwise in order to get the respective positions of the forward and backward components. The unbalancing factor is by definition e/d.

The Interpolar Fields of Saturated Magnetic Circuits

BY TH. LEHMANN[1]

Non-member

Synopsis.—*In this note, the question of the effect of assuming infinite permeability in the iron on the accuracy of calculations of the interpolar fields in electric machines is studied.*

One can do this very easily by replacing the saturated by non-saturated poles, covered by an infinitely thin sheet of current giving the same tangential component of the field along the surface of the iron. The field produced by this sheet of current, then, represents the difference between the exterior fields of the saturated circuit and of the non-saturated circuit.

In addition to this indirect method of estimating the influence of saturation, the sketch of the field between the poles and in the air-gap can also be directly developed by determining with the aid of the differential field, the point of indifference of the saturated circuit. A comparison of sketches obtained in this way shows that, for the same useful flux, the interpolar fields are almost the same in both cases. From these sketches and others which will appear shortly in the Revue Générale de l'Electricite, it is evident that the sketches and functional curves given by Messrs. Stevenson and Park, and Wieseman, in their very valuable work, can still be used even though the poles are saturated.

INTRODUCTION

SUPPLEMENTING my discussion of the very interesting papers presented by Messrs. Stevenson and Park, and Wieseman, at the last Mid-Winter Convention of the A. I. E. E., I should like to show briefly how, from the sketches of lines of force given by these authors, the distribution of the interpolar field can be obtained when the poles or the teeth are saturated.

I have chosen for this the magnetic circuit of a d-c. dynamo which has open armature slots. First, by assuming that the iron has infinite permeability, the sketch in Fig. 1 is obtained with four lines of no work, or gradients, which outside of the coil become lines of equipotential. This process of development is well known. In this case, the area of the coil has first been subdivided into four equal parts, and the last one of these, at the top, into eighths and sixteenths, etc., which makes it possible to see at a glance that each gradient[2] encloses that fraction of the total area which corresponds to its order. This is not sufficient, however, to obtain the exact position of the point of indifference[3] toward which the gradients converge and where the field is zero. It is necessary to make sure at the same time that the reluctances $R_1, R_2, R_3 \ldots$ of the parts of the same tube from one pole to the other are proportional to the ampere-turns $I\,n_1, I\,n_2, I\,n_3 \ldots$ enclosed by the gradients which cut off these portions of the tubes; otherwise the distance of the point of indifference from the side of the coil might vary from 1 to 2.

It is therefore necessary to check the relations $R_1 : R_2 = I\,n_1 : I\,n_2$, etc., as has already been shown under a different title in the *Revue Générale de l'Électricite* of September 22, 1923, p. 397.

When a portion of the tube is situated completely within the current-carrying region, the ampere-turns $I\,n_1$ included between the gradients which cut off that portion, are counted from the point of indifference to the line of force which forms the median of the portion of the tube under consideration. But if the portion of the tube falls partly in the interior and partly outside of the current-carrying region, it is preferable to count the ampere-turns $I\,n_1$ from the point of indifference to the first boundary line of the tube and add to that

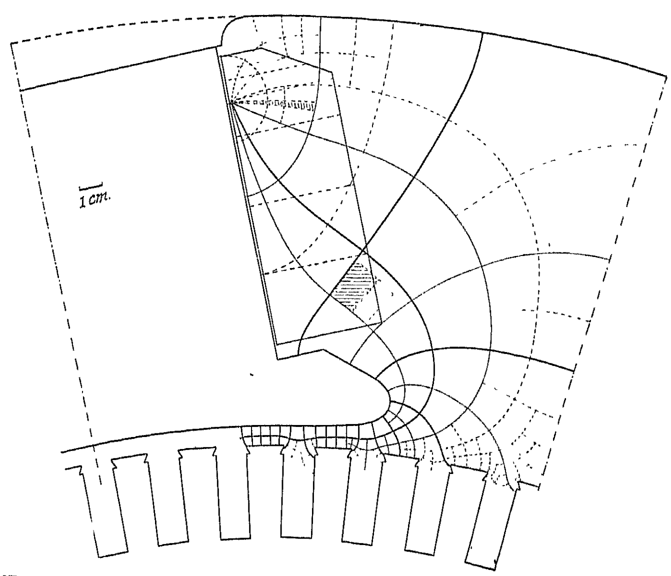

FIG. 1—SKETCH OF INTERPOLAR FIELD OF NON-SATURATED D-C. DYNAMO

value half ampere-turns contained in the portion of the tube itself.

Whenever the conductors in the portion of the tube form a rectangular section abutting against the two limiting lines of force, this reduction is applied, no matter what the thickness of the section, in the direction of the lines of force.

But when the current-carrying section does not cover the whole width of the tube from one line of force to the other, but only a fraction (n/m) of this width, it can be

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2. Called "lines of no work" by Stevenson and Park.
3. Called "kernel" by Stevenson and Park.

shown that it is necessary to deduct a fraction $(n/2\,m)$ of the ampere turns confined in the elementary tube. For example, one should deduct 3/8 of the current-carrying section that covers transversely only 3/4 of the width of the tube, regardless of the length of the section.

Finally, in the case where the contour of the coil cuts the tube obliquely, we can employ this same method by using judgment in replacing the oblique current-carrying zone of the tube by a rectangle of the same area, but of proportions so as to overlap the non-current-carrying zone as little as possible.

The magnetic field outside the field coil is Laplacian, and can be determined by subdivision into tubes of unit reluctance (curvilinear square tubes), according to the usual method. The sketch is commenced by full lines which are subdivided only in the regions where estimation of the elementary tubes would not be sufficiently accurate otherwise. I am inclined to think that it is not advisable to commence the sketch with

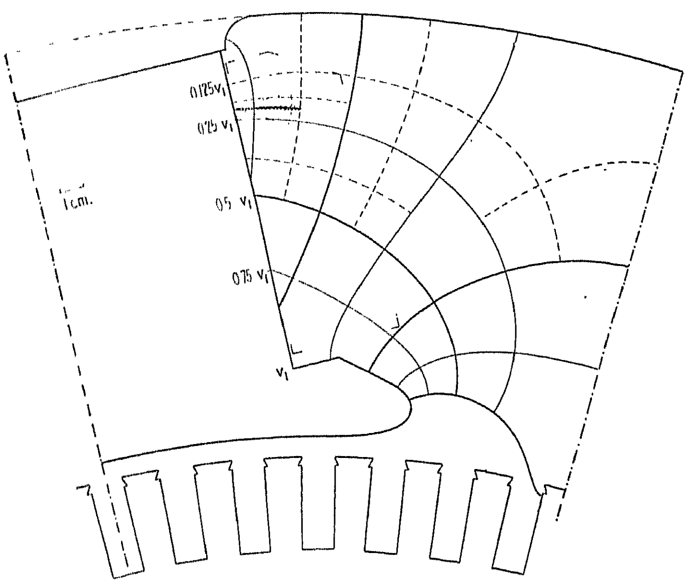

FIG. 2—ISOMETRIC SKETCH OF ADDITIONAL FIELD CAUSED BY SATURATION OF POLES

Assumed to be generated by an equivalent current sheet.

too fine a subdivision, which uselessly increases the necessary sketching and renders the localization of errors more difficult. The larger subdivision has also the advantage that, in rectifying the errors, account can more easily be taken of the effect of local retouching on the rest of the sketch which has already been traced.

THE ADDITIONAL INTERPOLAR FIELD CAUSED BY THE SATURATION OF THE POLES

Fig. 1 represents a sketch obtained in this manner. Now, assume that the pole is saturated in such a manner that, for the same useful armature flux, the pole core absorbs one-third of the total field pole m. m. f. $4\,\pi\,i\,n$, so that the difference of potential caused by the saturation of the pole will be

$$v_1 = \frac{4\,\pi\,i\,n}{3}$$

where the current i per turn is now in C. G. S. units. In Fig. 2, let us mark between the base and the top of the pole the points $0.125\,v_1$, $0.25\,v_1$, $0.5\,v_1$, and $0.75\,v_1$, calculated with the aid of the lines of flux in Fig. 1, and retouched as follows wherever necessary.

It has been shown in Sections III and IV of the mentioned article, that the field outside the iron will remain unchanged if the saturated core is replaced by a non-saturated core covered with an infinitely thin sheet of current. The current j per unit length must satisfy the relation:

$$4\,\pi\,j = \frac{\partial v}{\partial x}$$

in such a way that at the height x of the pole measured from its base, one will have:

$$v_x = 4\,\pi \int_0^x j\,d\,x$$

where v_x designates the superficial potential at this point caused by saturation. This equivalence, it is well understood, cannot be extended to the field in the interior of the iron, in which we are not interested here.

On account of this, the problem can be considered as follows. We can consider the interpolar field as resulting from the superposition of fields generated by the actual current in the field pole coil and by the counter-magnetomotive force of a sheet of current corresponding to the actual saturation, assuming in both cases that the iron is infinitely permeable. It is sufficient, therefore, to superpose on the sketch of Fig. 1, which was obtained for $\mu = \infty$ in the iron using the field current which would be required for the saturated pole, another field produced by the sheet of current, also calculated for $\mu = \infty$ in the iron. The sum of these two fields will give us the actual resulting field in the interpolar space and in the air-gap when the core of the field pole is saturated. If the field spider or yoke is also saturated, the sheet of current would naturally be prolonged along its surface.

The sketch corresponding to the sheet of current is very easy to secure because it is entirely Laplacian and the starting points of the equipotential planes $0.75\,v_1$, $0.5\,v_1$ . . . are known in advance, and in addition, the lines of force in the air-gap near the neutral zone differ only slightly from those of Fig. 1. Generally, such a sketch requires only a few minutes.

But this is not all. We gain, at the same time, a method of predetermining the kernel, or point of indifference, when the pole is saturated.

Utilization of the Difference Field for the Pre-Determination of the Point of Indifference

Since only equal and opposite fields annul each other, it is only necessary to search for the neighborhood where the gradients have the same direction and where the fields in Figs. 1 and 2 have the same intensity. Since the point of indifference must be in the interior of the coil, we notice immediately, when superposing Figs. 1 and 2, for example, against a window pane, that the gradients of Fig. 1 are tangent to the potential lines in Fig. 2 in the narrow slice which has been cross-sectioned vertically; see Fig. 1. The tangency continues far enough so that it is well to mark off a slice by the two gradients of Fig. 1, which coincide with only slight deviation with the potential lines of Fig. 2. It is only necessary now to compare the intensities of the fields. In Fig. 2, we see that the potential line on which the new point of indifference should be found is located in the square, the bases of which have a difference of potential $v_1/8$, and the lines of force a length of 1.95 cm. Assuming that the current density i_0 is $1/4\,\pi$ C. G. S. units the magnetomotive force of the whole field coil will be, for the scale of Fig. 1, 51 C. G. S. units, and that of the fictitious sheet of current 51/3 C. G. S. units, so that in the square tube under consideration in Fig. 2, the field H expressed in C. G. S. units is:

$$H = \frac{51}{3} \cdot \frac{1}{8} \cdot \frac{1}{1.95} = 1.10 \text{ C. G. S. units}$$

If one compares in Fig. 1 the curvilinear sector formed by the gradients, which embrace the fourth and the eighth part of the section of the coil, to a circular sector, the radius of such a circular sector must be, according to a well-known relation, $r = \frac{2\,H}{4\,\pi\,i_0}$, and remembering that $i_0 = \frac{1}{4\,\pi}$ C. G. S. units is the assumed current density, we then have:

$$r = 2\,.\,1.10 = 2.20 \text{ cm.}$$

and since the center of the equivalent circular sector falls one mm. behind the point of indifference, of Fig. 1, the new point of indifference will be found 2.10 cm. distance from the old one on the curved line bisecting the small cross-sectioned slice of Fig. 1.

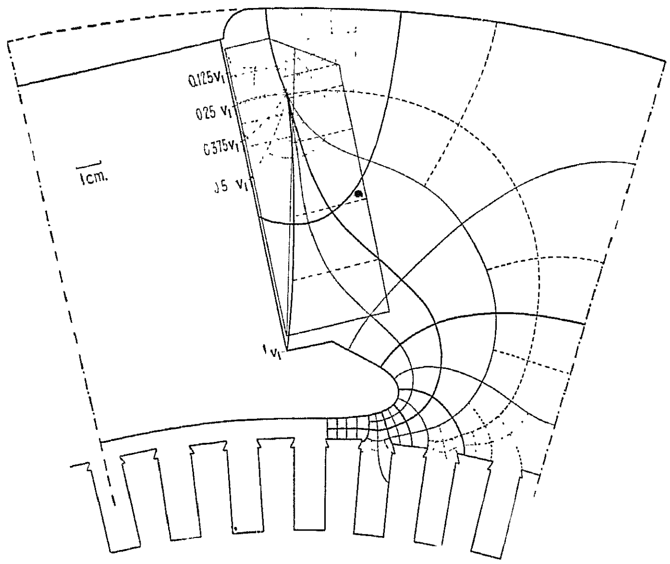

Fig. 3—Sketch of Interpolar Field of Dynamo Shown in Fig. 1, When Pole is Saturated

The point of indifference has been moved toward the interior of the field coil. The ampere-turns on the left of the gradients issuing from the points v_1, are consumed in the pole; and those to the right of these gradients are absorbed by the air-gap.

Direct Development of the Interpolar Sketch When the Poles are Saturated

Since we now know the point of indifference when the pole is saturated, we can easily develop the sketch of the interpolar field shown in Fig. 3, by dividing the area of the coil in the ratio 1:3 by a line which starts from the lower left corner of the coil. In this particular case, the point of indifference will be to the left of this line, and it is evident that the gradient which starts from the point v_1 of the pole core must be a little further to the right than the dividing line. The curve of this gradient will be given to us by the condition that on both sides of it the tubes of the same parameter must join without discontinuity, which makes it necessary to move the horizontal dotted lines which divide the coil in aliquot fractions sideways from this gradient until the proper concordance is obtained. The gradients which start from the pole core are easy to trace, since they join the points v_1, 0.5 v_1, 0.25 v_1, and 0.125 v_1, with the point of indifference.

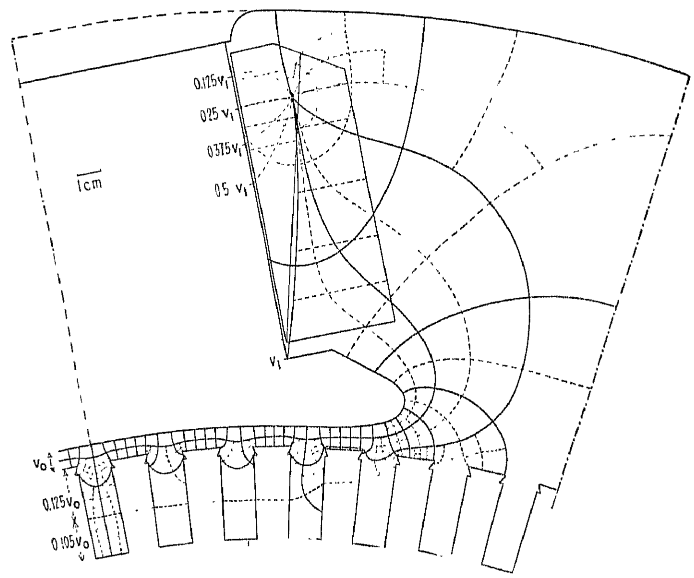

Fig. 4—Lines of Force and Gradients When Poles and Armature Teeth are Saturated

The ampere-turns to the left of the gradients starting from the points v_1 are absorbed by the pole; and the ampere-turns to the right by the air-gap and the armature teeth.